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FLOOD FLOWS

A STUDY OF FREQUENCIES AND MAGNITUDES

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BY

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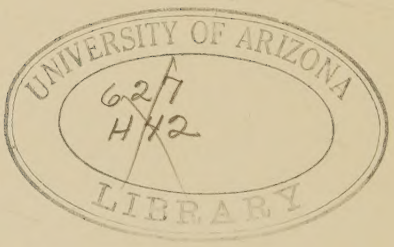

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PREFACE

For more than twenty years two related lines of study have been carried on in the engineering office of Hazen & Whipple. One relates to the size and recurrence of flood flows, the other to the required size of impounding reservoirs to maintain certain rates of flow during dry periods. Both have involved the same or similar mathematical problems in statistics and probabilities and in the use of skew curves. Methods developed in one have frequently been advantageously applied to the other, but there are fundamental differences, and the two studies have always been kept separate. The present work relates to flood flows.

Nearly everyone in the office of Hazen & Whipple during this period has contributed more or less to these studies. The author's younger brother, Richard, was one of those who helped in the early days. Weston E. Fuller, a partner, was an early student and published a paper which reflected the office practice up to the time of its presentation to the American Society of Civil Engineers.[1] The methods set forth in Mr. Fuller's paper have been added to and perfected with the lapse of time, but the basic method is still used as the most satisfactory available procedure.

To mention only a few of the engineering assistants who have worked at this problem: Richard Eurich added to the early development after Mr. Fuller's paper; Frederic H. Hapgood has contributed to the mathematical and skew curve studies; Albert P. Loriot has done most in collecting data and in making the calculations, has read the manuscript of the present work, and has made or checked all of the calculations contained in it.

During this twenty-year period the subject has always been kept active in the office to be taken up by the author and by his assistants whenever intermission in professional work per-

[1] Transactions Am. Soc. C. E., Vol. 77 (1914), p. 564.

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mitted. Every now and then a new dam has been built or some flood problem has come up that involved making estimates of probable flood flows. In each such case the opportunity has been utilized to revise what has gone before, to add to it, and to bring it up to date, thus contributing to the study.

During these years other engineers have been studying the flood problem and the methods of treatment. Each new paper in the Society Proceedings bearing upon the subject matter and each new treatise on statistics has been examined for material or methods that would aid in the development of the subject and in leading to better methods of estimating flood quantities.

The object of the present work is to gather in one compact presentation those methods previously published that seem most helpful; some of the basic data arranged in convenient form for reference; to add here and there some scraps of information not elsewhere easily obtainable; and to mix in a little of the author's philosophy in regard to the interpretation of the data and the application of the results.

In this presentation only relatively simple mathematical processes have been used. Graphic methods are largely depended upon that involve practically no mathematics after the basic method of plotting is established. The reader who wishes to follow the mathematical methods further will find abundant material in papers published by the American Society of Civil Engineers and in textbooks of probability and statistics to which reference is made.

ALLEN HAZEN

NEW YORK,
September 6, 1929.

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FLOOD FLOWS

A STUDY OF FREQUENCIES AND MAGNITUDES

CHAPTER I

INTRODUCTION

As years go by, the damage from floods is increasing. Many believe that floods are greater than they used to be owing to the cutting of forests, increased agricultural drainage, and other conditions resulting from the occupation of the land by man. On the other hand the best evidence available indicates that even before the country was occupied by white men there were floods as great as any that have occurred in recent years. At any rate the increase in the amount of damage from floods has been occasioned more by the increased occupation of areas that are sometimes flooded than by any increase in the volume of flood flows.

Flood Areas and Flood Frequencies.—The land along any river may be divided into three parts:

(1) The river channel, which all agree ought not to be encroached upon.
(2) The middle land, usually dry but sometimes flooded.
(3) The high land above all floods.

It is the increased occupation of the middle land that causes most of the trouble.

Study of floods and flood flows brings home the fact that there is no such thing as a maximum flood. Instead, there is a succession of floods of ever-varying size.

There is a flood of such size that it may be expected to occur every year. There is a much greater flood that may be expected to occur, on an average, once in ten years, not at

regular ten-year intervals, but say ten times in a century. A still greater flood may be expected as often as once in a century, and it may be assumed that there will be still greater floods that occur only at intervals of several or many centuries.

It would be theoretically possible to draw a line down the bank of a stream above which there would be only one chance in ten that water would rise in any one year, and to draw another and higher line above which there would be only one chance in a hundred, and so on for higher and less frequent floods. These imaginary lines may be referred to as the *ten-year flood line,* the *hundred-year flood line,* the *thousand-year flood line,* etc.

If these lines could be marked across the landscape so that all could see them, much of the loss by floods would disappear, because people would then protect themselves.

The first settlers in any community are apt to be cautious and to locate upon high ground, where there is little danger of being flooded. As communities increase in size the high land that is safe from flood becomes more valuable than the lower land that is sometimes flooded. Knowledge of flood conditions is lacking and memories are short. Low lands convenient for manufacturing, residence, and other purposes are tempting to those who lack capital to secure better sites, and especially to those who have not the foresight to see the damage that will result, sooner or later, from the occupation of low land. The town originally built above the hundred-year flood line gradually extends down to the thirty-year and even to the ten-year flood line.

Of course it cannot be held that the whole middle area, especially where it is large, should be reserved. Some of it can be reclaimed by filling to higher and safer levels, some may be protected by dikes, and some businesses may be so conducted that damage by flooding will be limited and it will pay to take the risks of an advantageous site that will not be flooded too frequently.

But it must be recognized that it is the increasing use of land in the middle, or flood zone for business purposes and for residence that is responsible for the great increase in damage from floods.

The occupation of this middle zone has an indirect influence

in increasing the height of floods resulting from a given flood discharge. Highways, trolleys, and railroads are built across the flood plains of rivers, leaving channels or passages only large enough to carry ordinary floods. An extreme flood passes, but with a loss of head that means a higher water level in the reach above. Warehouses, factories, and fences built in the flood areas of rivers all add resistance to the passing water. One such structure may have little influence, but when the number is increased until additional points of resistance are presented to the flowing water all the way, the aggregate effect is to make the water rise considerably higher than it otherwise would have done and to increase the resulting damage.

Among remedies suggested and discussed for prevention of floods is one very simple one, which perhaps receives less attention than it deserves. That relates to the prevention of flood damages but not to the control of flood flows. It consists simply in refraining from occupying land that is sure to be periodically flooded. It may not be practicable to do this in all cases, but along many rivers, at least, there are, on land high enough to be above danger, ample sites for all the business that needs to be accommodated.

The lands that are ordinarily dry but that are sometimes submerged need not become waste land. There are uses to which they may be put. Along the rivers that flow through cities they are appropriately used for park purposes. Parks can be built and maintained so as not to interfere with the occasional use of the full flood channel. The parks will be damaged sometimes by floods, but the damage will be relatively small and easily repaired. Think what an improvement it would be if a city now built in part in the flood plain of a river could be moved back to higher ground with the river bank and the lower part of the occasionally flooded area laid out as a public park with ample roads and drives. Arrangements of this general character are found in some European cities and less frequently in America.

The substance of the above paragraphs appeared in "Engineering Record" for October 11, 1913, as comment upon a number of disastrous floods shortly before that time. The sixteen years that have passed since they were written have served to emphasize the conditions that were then noted.

Records as Basis of Flood Study.—A great quantity of water flowing in a stream makes a flood. The rate of flow in a stream is always changing. It goes up with rains and melting snows and down with dry periods and down still more in long-continued drouth. It usually goes up rapidly and down slowly. Sometimes it changes upward to a destructive flood. The graph of flow never repeats. No flood and no combination of flows is like those that have gone before. There is always something different.

If we have a thirty-year record of the flow of a stream at a given point—which is about as long as flow records average in the United States for those streams fortunate enough to have them at all—it is certain that in the thirty years to come the mean flows and the flood flows will be different from those in the record period. Another period may contain a greater flood or it may not contain one as great. What has happened in one such period is not to be accepted as a close guide as to what may be expected in another, but it may be, and often is, almost the only guide that is available.

Some catchment areas have greater flood producing capacities than others. Steep slopes and impervious soils shed water rapidly. In flat sandy country much of the rainfall from great storms is absorbed and held temporarily, and the floods produced will be less. Lakes and reservoirs retard flood flows, and by spreading reduce the maximum rate of discharge.

In speaking of floods, all things are relative. The basis of comparison is what a particular stream has done in the past and does every once in a while. A great flood is one that is great as compared with the floods that have gone before. It may not be great at all compared with similar floods on another stream.

It is often necessary to make an estimate of what future flood flows may or must be provided for in order to secure reasonable safety of engineering structures and of human occupants of valleys through which floods pass. There has been a great deal of study of this problem of estimating flood quantities and there is a considerable amount of literature bearing upon it.

For the present, and for the future, the greatest promise lies in the study of the records of flow kept continuously at gaging

stations maintained by the U. S. Geological Survey, by state hydrographic bodies, by water power companies, and by municipalities in connection with water-works. Records of continuous flow of streams at enough stations and through long enough terms of years are now available so that there are data to give a notion of the variation in and frequency of recurrence of flood flows. Such data are increasing rapidly in number. Each year there is a better base for the studies we now desire to make.

We have thus a mass of data as to daily flows of many streams through considerable periods, including the records of the highest rates of flow during those intervals. The problem is to handle the data so as to make them throw all possible light on flood quantities. No Chinese puzzle can compare in interest with trying to arrange these data in a way to make them tell truthfully the story, and all of the story, that they are capable of telling. The importance of the subject is great, and our utmost effort may be made in solving this riddle.

Aside from the practical results that are involved, the joy of solving an intricate problem of this kind, or at least of making some progress in its solution, is enough to compensate one for the tedious calculations that are frequently required. The tendency is to use short-cuts and to try for methods that will produce directly the desired result, but the step may be too long to be covered at one operation. It may be better to set up some intermediate points comparable to the turning points in leveling. These intermediate points may have no great significance in themselves. Their importance lies in the fact that relations between them and the data, on one hand, and between them and the flood quantities, on the other, may be established. It is therefore proposed to take off a number of intermediate values which will serve as stepping stones in the calculation of the desired flood quantities.

To anticipate the method briefly, it is proposed:

1. To find the average of the annual floods and to find a coefficient which expresses the relations of these average floods to the size of the catchment areas from which they come.

2. To find the coefficient of variation of the annual floods, and

3. To calculate the coefficient of skew for the same values.

These three values, all of which are computed by methods to be presently described from the records of a stream that has been gaged for a number of years, serve to give indications sufficient to draw a line to represent the probable periods of recurrence of flood flows of various magnitudes.

The first, or *flood coefficient,* fixes the height of the line above the base; or in other words, gives a notion of the general magnitude of floods on that particular stream.

The second, or *coefficient of variation,* gives the inclination of that line, indicating the ratios of large floods to average ones.

The third, or *coefficient of skew,* gives a measure of the curvature of the line, upward or downward.

With these three constants, the line representing floods for the particular data from which they were derived may be reproduced with a fair degree of accuracy.

The next step will be to compare the records of a number of streams in the same locality and of records from different localities and to see what inferences as to flood conditions may be drawn from them.

CHAPTER II

DEFINITIONS OF FLOOD QUANTITIES

Floods may be described in a great variety of ways. The selection of a method must be arbitrary. It is made with reference both to the work in hand and to the data available.

Floods may be defined either by gage heights or by water quantities. Gage heights are more generally used by the public and are more intelligible to them than water quantities. If river channels were fixed and unchangeable there would be a good deal to be said in favor of studying gage heights rather than flood quantities. But river channels are seldom the same through a long term of years, and equal quantities of water at different times produce different gage heights because of channel changes.

As a practical matter, the volume of flood flows must be the basis of any comparative study of floods. They furnish the only basis for accurately comparing floods of one time with floods of another time on the same stream, and especially for comparing the floods of different streams.

Water quantities must be translated back into gage heights when the occasion requires and this is to be done on the best local data that may be available.

Floods Classified.—Some definitions of flood quantities are necessary at the outset:

The *maximum flood* is the greatest rate of flow at any minute during the entire record period.

The *maximum annual flood* is the greatest rate of flow at any minute during any one year.

The *average maximum flood* is the average of the maximum annual floods for a series of years, one for each year.

The *maximum two-hour flood* is the highest average rate through any consecutive 120 minutes that can be found in the record period.

The *annual two-hour flood* is the highest corresponding rate in any one year.

The *average two-hour flood* is the average of the annual two-hour floods, one for each year in the record period.

A similar form of statement may be used for any other period, six hours, twelve hours, twenty-four hours, etc. It may be extended to five days, ten days and to monthly, and even to annual flows. In the latter case the figures represent the entire flow of the stream.

The *maximum one-day flood* is the highest average rate of flow any one record day, the day being taken between the hours regularly used in making up the record of flow. It differs from the maximum twenty-four-hour flood in that the twenty-four hours used for the calculation correspond to those used in making up the daily records, and are not selected to give the highest average rate for any twenty-four consecutive hours that can be found.

The *annual one-day flood* is the greatest average rate of flow in one record day within the record year.

The *average one-day flood* is the average of the annual one-day floods for the record period, one for each year. This is the value that will be commonly used as a basis for estimating other floods. For simplicity of statement it will be called the *average flood.*

The calendar year is usually the most satisfactory basis for making up the schedules of annual floods; but January 1 has no special merit as a starting point, and if the gaging records have been tabulated in years beginning on July 1 or October 1, there is no objection to selecting the annual floods on such basis. In a short record period, cut on different dates, and therefore having different beginnings and endings, there would be small accidental differences, as often in one direction as in another. These would be less as the record period was longer; and probably in no case would such difference be significant.

The average flood is the first important base line. Its value is to be computed for each stream from its own record, and it serves as a basis for estimating the other kinds of floods for which values are to be found. In general all the other kinds of floods will be estimated by multiplying the base value by appro-

priate factors. These factors must be ascertained from the available data.

The twenty-four-hour flood will always be greater than the one-day flood. Usually it is only a little greater, but sometimes the difference will be considerable. If records permitted it, the twenty-four-hour flood would be preferred for use. However, its value can be correctly ascertained only where there is a complete automatic record of flow at all hours and then by study of the original data. Records of this character are so few that this basis is not generally available at present.

On the other hand, one-day floods may often be taken from published tables of flow. Nearly all of the available data are in a form to permit these values to be taken for use. As a practical matter this basis is satisfactory. The twenty-four-hour flood would be preferred if the values were generally available, but as they are not, very good use may be made of the other.

The ten per cent chance flood is the flow of water such that it will probably be exceeded on an average in ten per cent of the whole number of years. That is to say, the limit will be passed once in ten years or ten times in a century. A flood of this size has commonly been referred to as a ten-year flood, but the term is not altogether accurate and leads to misconception.

Floods above the ten per cent chance limit, or any other limit, do not occur at regular intervals, but are apt to come in groups. That is to say, there may be a number of them within a few years followed by a considerable period in which no floods of such magnitude occur.

The term ten per cent chance flood may be applied with additional words to designate floods of any of the classes above defined. That is to say, we may have a ten per cent chance maximum flood, a ten per cent chance one-day flood, etc. Unless otherwise noted the term is taken as referring to the one-day flood.

The term *ten-year flood* has been sometimes used with a different definition from that now followed; namely, to designate the average of all the floods above the ten-year limit. It will be well to note this difference carefully to eliminate danger of confusion.

The ratios between the floods defined in this way and those now defined may be ascertained by examination of the plottings.

Approximately the average of all the floods above the ten-year limit will be equal to the flood at the twenty-five year limit, and the average of all the floods above the one hundred-year limit will be equal to the flood at the two hundred fifty-year limit, and others in proportion.

The one per cent chance flood is the flow of water such that it will probably be exceeded on an average in one per cent of a whole number of years. That is to say, the limit will be passed once in a hundred years or ten times in a thousand years.

In the same way floods of any other degree of frequency may be represented by the decimals or per cent chance of their probable occurrence in any one year.

This form of expression is not limited to the ten per cent, one per cent, etc., but may be used for any intermediate degrees of frequency that may be desired.

The common practice of referring to such floods as the ten-year floods, thirty-year flood, one hundred-year flood, etc., is convenient. The number of years and the decimal representing the chance of occurrence in any one year are reciprocals of each other.

There are a number of practical reasons why it is better to speak of the one per cent chance flood rather than of the one hundred-year flood, although the two expressions, as we use them, mean exactly the same thing.

The term one hundred-year flood is apt to carry the impression of something that is going to happen after a hundred years, or at least after a very long time, and so remote that people in this generation do not need to worry about it. This is not the fact at all. Such a flood is just as likely to occur next year or in any year as it is after a long interval.

Another reason why this form of expression should not be used is that in such very long terms as one thousand years and ten thousand years there may be climatic changes. This will be referred to in Chapter XVIII. It is quite possible that there will be pulses or cycles or changes in flood conditions within such periods, and floods may be greater or smaller on an average in such a time interval than can be inferred from present data, derived, as most of the data are, from records in a relatively short term of years in the immediate past.

The terms ten per cent chance flood, one per cent chance

flood, etc., do not refer to any particular floods but rather to a limit which corresponds to a certain chance of recurrence in any one year.

It is also interesting to note in examining actual records, especially from small catchment areas, that the maximum floods of the different classes do not always come on the same day or even the same month. It will sometimes happen that the maximum flood will be observed on a day of a short hard rain, whereas the maximum day's flood will occur at another season of the year with melting snow or long continued rain which produces more total runoff but not as high a peak. In any event, the highest flood of its class is to be selected in each case regardless of the time of its occurrence within the period of record.

The *primary flood* is the largest flood of its class in a record year. There is always one primary flood each year and no more.

Secondary floods are all floods that are not the maximum of their class in any record year.

When the data for a term of years are assembled, it is found that many secondary floods are larger than some of the primary floods. There is always a temptation to cut out low primary floods and substitute high secondary floods in computing the annual flood. In the procedure now followed this tendency must be resisted.

An independent study including secondary floods may be made if desired. It is a perfectly proper procedure, but a different one, and will follow different rules. It will be described in Chapter XII.

Floods may be stated in any convenient unit of flow. Cubic feet per second is the unit commonly adopted in America, but million gallons per day is used in many water-works records. In taking off flood data it is better to follow whatever unit is used in the record under examination, avoiding both the labor and the chance of error in converting. The mean flood, however, should be converted to cubic feet per second to facilitate comparison with other records.

A series of factors may be found from the actual data of flood flows and applied to the mean one-day flood to produce estimates for the ten per cent chance flood, the one per cent chance flood, and for any other limits that may be desired.

Other factors may be applied to the mean one-day flood to find the corresponding maximum flood, the two-hour flood, etc. By applying both factors, an appropriate one of each kind, estimates may be made of floods for any time interval and for any degree of rarity.

Probability or Statistical Methods.—The annual one-day floods for a term of years form a series of numbers which may be examined by statistical or probability methods. The same may be said of the annual maximum floods or of any of the other cases of annual floods enumerated above.

It is not the intention to go into any discussion of the theory of probability or into description of commonly used methods, but reference is made to textbooks for further information upon those points. It may be stated, however, that such methods are believed to be applicable to this study, and the methods of procedure will be briefly described.

It is not to be supposed that these flood data follow exactly any law that can be now stated, or that all of them follow the same law. The whole procedure is one of approaching directly in a graphical way a difficult problem in the endeavor to obtain the most reliable indication that can be drawn from the data at hand.

This problem is more difficult because the data at hand are frequently so limited in number that they are inadequate to furnish a definite and accurate answer to the problems that are presented. Nevertheless, the data may be all that are available in a given case, and it may be our duty to try very seriously to learn all that we can from them.

In making studies of this kind, and in stating the results, there is frequently an appearance of accuracy that is not warranted by the character and extent of the data. No result can be more accurate than the data on which it rests, and in this case the data cover short periods and the estimates long ones, so that answers may be even less accurate relatively than the data on which they rest.

Calculations of this kind, therefore, should not be taken as leading to definite and final results. Rather they should be used as aids to judgment. The results are to be used in the light of all the modifying conditions that may exist, and of all the data from other streams that may be applicable.

CHAPTER III

METHOD OF PLOTTING ANNUAL FLOODS

When the maximum one-day flood has been ascertained each year for a number of years, the numbers representing these flows may be plotted and examined by graphic methods. In doing this the maximum flows, one for each year, are arranged for plotting in the order of size. Floods may be plotted directly as cubic feet per second or they may be expressed as ratios to the mean flood.

If direct results in cubic feet per second are desired from the record of a particular stream, the plotting may be made directly in cubic feet per second. If, on the other hand, a general study and comparison of different streams is desired, the ratios must be used. When the ratios are used, they may be converted back to cubic feet per second by multiplying them by the mean flood. The use of the ratio method, therefore, in the end, gives everything that could be obtained by the direct plotting.

Plotting Paper.—The plotting paper is graduated decimally and the position of any point in the series may be found by the equation:

$$P = \frac{2m - 1}{2n}$$

where n is the total number of terms in the series and m is the number of the term that is to be plotted.

Logarithmic probability paper is used uniformly in the present work. It is selected because in our experience it has been the most satisfactory of the various kinds tried.

Logarithmic probability paper, it may be stated briefly, is laid out in such a way that if the logarithms of the terms plotted upon it form a series following the normal law of

error, the terms plotted as above described will all fall in a straight line.

Flood data do not exactly follow this law, but in many cases they approximate it rather closely, and, in general, this kind of paper is well adapted to the service.

Plotting Points and Drawing Curves.—The plotting of the points in this way can be used as a basis for drawing a line which gives a notion of the frequency of recurrence of large floods.

The line may be drawn in the old-fashioned way by the eye or by stretching a string in the endeavor to draw it so that an equal number of points are above and below in the whole line and also in each major part of the curve. If it fits the points well, it may be extended moderately to rarer and more remote flood chances. Refinement in the method will be taken up in a subsequent chapter. In any event, the intersection of the line representing the data with the vertical line of the plotting paper representing any given chance of recurrence will serve as a basis for an estimate of a flood of that degree of rarity.

In subsequent chapters there will be presented methods for determining the probable position of a number of points in a line that may be drawn to represent few and scattered data that do not perfectly line up. These additional methods are supplementary to the graphic method now described and do not supersede it in any way. Their purpose is to reduce as far as may be the difficulties in drawing lines to represent the most probable values that can be obtained from the data at hand, especially where such data are meagre and scattered and when important estimates must be based on them.

Example.—As an example of the method of handling and plotting data, a 10-year record of floods in *Little River* at Springfield, Mass., is presented in the table on p. 15 and in the plotting, Fig. 1, on p. 16. This is a shorter record than is usually plotted, but it illustrates the method as well or better than a longer one.

The line drawn on this plotting is graphic only and no refinements are attempted. A longer record of the same stream is plotted in Fig. 7, p. 57. The differences between the shorter and longer records are marked and illustrate the limitations of short term records.

A word may be said regarding the origin and history of

FLOOD FLOWS IN LITTLE RIVER, SPRINGFIELD, MASS., WATER-WORKS FOR TEN YEARS ENDING 1919

Year	Maximum flow for one day, mgd., in the order of occurrence	Same arranged in order of size	Same expressed as ratios to the mean of the series	Decimal positions for plotting
1910	1242	1845	1.521	5
1911	1280	1490	1.228	15
1912	1304	1469	1.211	25
1913	1119	1304	1.075	35
1914	1490	1280	1.055	45
1915	1845	1242	1.024	55
1916	863	1119	0.922	65
1917	878	878	0.724	75
1918	641	863	0.712	85
1919	1469	641	0.528	95
Average.....	1213	.....	10.000	

probability paper. Paper of this description with an arithmetric scale was first used in 1913, and described in a paper by the author on "The Storage to be Provided in Impounding Reservoirs for Municipal Water Supply"[1] as follows:

The spacing of the lines for this paper was computed from figures taken from probability curve tables, and arranged so that the line which represents the summation of the probability curve, when plotted on it, is straight. If the data for any series correspond strictly with the normal law of error, the points plotted on this paper will all be on a straight line. If the data approximate the normal law of error, the line through the points will approximate a straight line. Even though the deviation from the normal law of error is considerable, a line with only a moderate curvature may represent it fairly well.

It was soon found that many kinds of data when plotted upon arithmetic probability paper fell in lines with considerable curvature, and this led to an effort to find some form of plot-

[1] Transactions Am. Soc. C. E., Vol. 77 (1914), p. 1549.

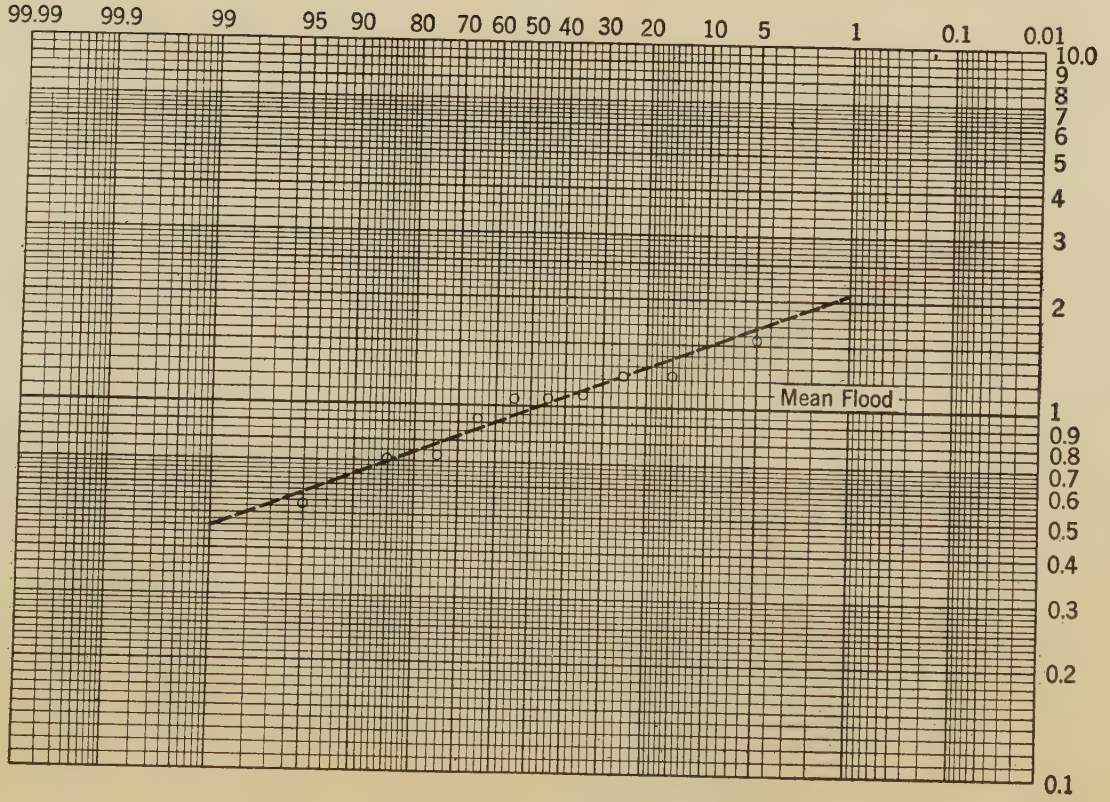

FIG. 1.—Illustrating Method of Plotting Flood Flows.

ting paper that would permit such data to be shown with less curvature.

One of the methods tried was to substitute a logarithmic scale for the arithmetic scale, the lines on the probability scale remaining unchanged.[2] On paper ruled in this way a series such that the logarithms of the numbers follow exactly the normal law of error will plot as a straight line.

It was soon found that paper of this description was better than arithmetic probability paper for many uses, among them the plotting of flood flows.

The use of probability paper may be compared to the use of logarithmic paper, which has become general and is most helpful. Logarithmic paper is seldom used for the solution of problems when the relations follow exactly the law on which the paper is laid out. If the data exactly followed that law, the problem could be otherwise solved without recourse to the use of it.

The greatest use of logarithmic paper is in handling data that approximate but do not exactly follow the law on which the paper is laid out. Because the data approximate that law, the lines resulting from plottings are direct and do not have excessive curvature. Because the data do not exactly follow the law the lines are not straight but have moderate curvature. The use of logarithmic paper affords a means of plotting and graphically determining certain relations. Its sole merit is that with data that approximate the law, the lines representing them are near enough to straight so that they can be drawn with assurance and comparative accuracy not obtainable when the same data are plotted on some other kind of cross-section paper.

This illustrates the author's point of view in regard to the use of logarithmic probability paper. These flood flow data do not follow exactly the law on which this paper is laid out, but they do approximate it to such an extent that the use of the paper is a material aid in correctly representing them and in drawing inferences as to the chances of recurrence of floods above certain limits.

Both arithmetic and logarithmic probability paper are available, being published and sold by the Codex Book Company, 461 Eighth Avenue, New York City.

[2] Transactions Am. Soc. Vol. C. E. 77 (1914), p. 1666.

Logarithmic probability paper is printed in two forms; one extending to the 0.01 per cent limit in each direction and suitable for general use, and a special form extending to extreme values at one end with a corresponding shortening at the other which is adapted to plotting series with more than five thousand terms and for estimating extreme values near one limit.

Most of the figures used in this work are based upon the different kinds of probability paper and inspecting the figures will give an idea of the various forms and their uses.

Fig. 48, p. 113, is based on arithmetric probability paper and shows one whole sheet. Fig. 1, p. 16, is based on the usual logarithmic probability paper. Figs. 5 and 6, pp. 54 and 55, show the extreme value logarithmic probability paper. Figs. 8 to 41, beginning on p. 75, are made on logarithmic probability paper but using only so much of the sheet as is required to accommodate the data to be shown in each case.

CHAPTER IV

DATA AVAILABLE FOR STUDY

One hundred and nine flood flow records, each one covering twenty years or more, have been collected and are used in the present study. Most of these records have been taken from the published tables of the U. S. Geological Survey. It is unfortunate that these results cannot be more promptly published. They are normally several years in arrears, and records, at best too short, are correspondingly shortened.

The Geological Survey has not only published its own gagings, but has collected, revised, and published gagings made by others; and thus has rendered service in preserving records that otherwise would not be available.

The figures of the U. S. Geological Survey have sometimes been revised, and later publications do not in all cases correspond exactly with earlier ones. Revision of rating curves and correction of errors must account for these differences. In general, the latter results are presumed to be more accurate.

There are numerous records of flow from other sources than the Geological Survey that have been used. These include some of the best records. A few of these have been privately communicated but most of them have been taken from published sources.

Kind of Data to be Used.—Although the fact is quite obvious, it may nevertheless be well to state that all of the data used in one series must have been derived from conditions that did not change in any material way during the record period from which they were drawn. That is to say, if a reservoir is built on a stream which changes the flood quantities in a material way, the record before the reservoir was built forms one record, and the record afterward forms another; but the two should not be combined in a single record.

The diversion of water to irrigation ditches, and storage in small reservoirs on tributaries may be ignored in most cases—not because there is no change in the flood conditions, but because the changes, in the absence of evidence to the contrary, are presumably not great enough to affect the results materially.

In a few cases of small streams fully controlled by storage, the natural flow of the stream, as distinguished from the actual flow, is computed. The adjustments consist in adding storage to and subtracting depletion in reservoirs from the actual flow or draft. The adjusted record shows the actual water production of the catchment area by days. Such a record may be a most satisfactory one, and may be consolidated with a record of the natural flow of the stream before storage because the two parts are presumably on the same basis.

Storage reservoirs are being built all over the country and are resulting in changes in the régime of operation on many rivers, and these changes are going ahead at an accelerated rate.

Flood flow data, to be useful in general discussion, and to throw light on the nature of flood flows, must be selected in view of these conditions; on the other hand, it is impracticable, in most cases, to apply corrections, and small changes must be accepted as not materially changing the flood conditions.

Data Obtained from Other Sources Than the U. S. Geological Survey.—The Geological Survey data are so numerous relatively that it is well to record the sources of important items not so obtained.

The eighty-two year record of the *Merrimack River* at Lawrence, Mass., is the longest record we have. The volumes of the flood flows were compiled by the late R. A. Hale, Chief Engineer of the Essex Company, which owns and operates the dam and water power at Lawrence. The records are accurate and the calculations most carefully made.

During the great floods of 1872 and 1874, and at other times when the flows were smaller, General Ellis gaged the *Connecticut River* at several points near Hartford by means of current meters and floats. From these data he estimated the flows at Hartford, and prepared a table showing the discharge for each foot in height up to thirty feet. This table was published in the Report of the Chief of Engineers for 1875, Part II.

A rating curve based upon this table has been used, in connection with a record of maximum gage heights at Hartford, to compute the annual floods through a long term of years. This record from 1843 to 1913, with one year, 1892, missing, was prepared by Colonel George B. Pillsbury.[1] Data for subsequent years to complete the record have been furnished by Major F. S. Skinner, District Engineer. The record prepared in this way cannot be supposed to be very accurate, but it is of interest and value especially because of the long period of years covered. The records for the various years may be relatively more nearly correct than the determination of the quantity at any given elevation.

Colonel Pillsbury points out that, on account of the flat slope and tidal influence, the low-water discharge cannot be reliably inferred from the gage; but that the slopes at high water below Hartford are sufficient to render this gage a reliable indication of flood discharge.

The question may be raised whether there have been changes in the river channel during eighty-five years that would materially affect its hydraulic properties, and whether the gagings of 1874 may be projected back to 1843 and forward to 1928. The river from Hartford to Saybrook has not been extensively improved or otherwise changed and it seems likely that such changes as there have been have not been of a character to seriously impair the value of this record.

Another forty-four-year record of the Connecticut River is made up by a combination of records from Holyoke and Sunderland, Mass. The results at Holyoke are stated by Clemens Herschel from the Water Power Company records,[2] and those at Sunderland by gagings of the U. S. Geological Survey. The stations are not far apart and for this purpose they are used as constituting one record.

Three streams, *Perkiomen, Tohicken* and *Neshaminy Creeks,* were gaged for twenty-nine years in a most painstaking way with reference to their proposed use for the water supply of Philadelphia. This work was organized by Rudolph Hering and was carried out by competent engineers throughout the entire period. The records are probably among the most accurate that

[1] Transactions Am. Soc. C. E., Vol. 77 (1914), p. 674.
[2] Transactions Am. Soc. C. E., Vol. 58 (1907), p. 29.

we have. The figures that are used were taken from the publications of the Pennsylvania Water Supply Commission.

Two very useful records, one of the *Black River,* at Watertown, New York, for thirty years; and one, of a tributary, *Moose River,* for twenty-six years, were prepared by the collection and revision of available data by Edwin S. Cullings.

The thirty-one-year record of the *Passaic River* at Great Falls, N. J., was furnished by John H. Cook, Engineer and President of the Society for Establishing Useful Manufactures, a company organized by Alexander Hamilton, which owns and operates the water power. This is a very accurate record, and particularly interesting, because of the two remarkably large floods that occurred in two successive years.

The twenty-three-year record of the *Little River,* part of the Springfield, Mass. water supply, was obtained from stream gagings for four years, and the records of the flow over the intake dam for nineteen years. There is some storage in a reservoir on a tributary stream so that the figures are adjusted for storage and represent the maximum production of water in any one day during the calendar year. The record is kept by E. E. Lochridge, Chief Engineer of the Water Department.

The twenty-two-year record of the *Colorado River,* at Austin, Texas, was mainly furnished by D. H. Mead of Madison, Wisconsin, but two or three additional values from the U. S. Geological Survey have been added to it.

The twenty-eight-year record of *Alameda Creek* at Sunol, California, part of the Spring Valley Water Supply system, was furnished from the Company's records by G. A. Elliott, Chief Engineer. This represents conditions before the Calaveras Dam was built. Records for subsequent years could be secured but would not be pertinent as Calaveras Dam has since modified the flood flows. The data used represent substantially the natural flood flows of the stream. These gagings were very important, they have been subject to much engineering study and criticism, and the quantities have been determined with all possible accuracy.

The twenty-year record of the *Des Moines River* came from Alvord, Burdick & Howson of Chicago.

The sixty-four-year record of the *Columbia River* at The

Dalles, Oregon, was communicated by L. F. Harza, who states that he obtained the quantities from the U. S. Geological Survey records. However, as far as we have found, the data from which it may be obtained have not been published in full.

Records of the *Pemigewasset River* in New Hampshire and of the *Chippewa River* in Wisconsin were furnished by N. C. Grover, of the U. S. Geological Survey and Chairman of the Committee on Flood Protection Data of the American Society of Civil Engineers. These records, presumably based upon records of the Geological Survey, were arranged by Mr. Grover to permit use of the method of analysis now employed.

Numerous other data collected by this committee were understood to be arranged in the method to be described in Chapter XII. By that method floods above some arbitrary limit were listed whereas the annual floods below that limit were not included.

It has been the intention in all cases to use the one-day average quantities but it is not easy to get clear-cut definitions on old data, and unfortunately it cannot be asserted that all of the data now presented are based on that standard. Examination of original records and calculation sheets would furnish the only real answer and this has not been attempted.

Many water-works systems, power companies, and engineers have records of flows filed away in their archives from which useful records of flood flow could be prepared. Many gagings are started but for some reason are interrupted so that they are not complete enough to serve as a basis for estimating the entire flow of the stream and are not published because of their incompleteness. If the incompleteness includes the flood periods, they are of no use in studying floods; but if the missing numbers relate to low flows and periods when ice interferes with gagings, the flood record may be just as good as if the record were complete.

It is to be hoped that this suggestion will lead to the examination of many such incomplete records and to the ultimate addition of much useful material to the study.

Accuracy of Data.—No estimate can be more accurate than the data on which it rests. To obtain accurate ideas of flood conditions, the study must rest on sound data. It is not to be

expected that anything like precision has been or will be reached in measuring flood flows, but some degree of accuracy may be reasonably expected.

Most of the gagings used in the studies now presented are taken from the records of the U. S. Geological Survey. This body has for many years been charged with the duty of gaging and recording the flows of American streams. The methods used are no doubt as appropriate and accurate as could be selected for the conditions under which it is necessary to operate.

The method most commonly employed is water quantity measurement by the use of current meter gagings. The gaging place is selected where the channel of the river is, as nearly as may be, hard and stable and in the form of a prism that permits a regular flow free from eddies. A gage is established and the height of the water is observed at intervals or continuously through the record period. From time to time gagings with a current meter are made, these gagings representing different heights of water. The quantities found are plotted against the gage heights and in this way a rating curve is made.

With a record of gage heights twice a day or oftener, or continuously with a self-recording instrument, the rating curve is used to ascertain the rate of flow at the time of each observation, or at frequent intervals, and this is the basis on which the daily quantities are calculated.

Current meter measurements increase in difficulty as the flow is greater. Hoyt and Grover, both of whom have been long identified with the Geological Survey work and have had to do with establishing the methods of gaging, give a graphic picture of some of the conditions actually encountered in measuring flood flows. In their book, "River Discharge," they state:

> Measurements made at high stages generally consist of observations of surface velocity only. Areas must be computed from a standard section or from soundings made at a lower stage. Under these conditions extra precautions must be taken to secure data from which a reliable estimate of the flow can be made. On account of the great velocity and the presence of drift and cakes of ice, it is often practically impossible to make a good meter measurement. Meter observations of 10 to 30 seconds may, however, frequently be obtained when there is considerable drift, but great care must be exercised that the meter is not damaged. If a weight of more than 30 pounds is required to submerge the meter, cotton or

manila line must be used in conjunction with the insulated cable for supporting the meter. Extra heavy and large tails with both horizontal and vertical vanes must also be attached to the weights in order to keep the meter headed properly into the current.

If there is much drift, however, it is generally advisable to use the float method, the drift serving as floats. In this event a base line is laid off on the shore, range poles are set on one or both banks, and the surface velocities are obtained by observing the time required by the drift to pass over this measured course in various parts of the channel. In other instances, it may be practicable to determine the slope of the river for a considerable distance. If a level is not at hand, marks may be made and the slope determined at some future visit. When possible, two of these methods may be used and a check thus obtained upon the work.[3]

This gives a notion of the great difficulty of making accurate gagings of flood flows. It does not help us with the still more important problem of estimating floods that are not gaged. Times of maximum flood cannot be known much in advance. Considerable preparation and equipment are needed to measure them, and undoubtedly it happens that many of the largest floods pass without being actually measured.

Furthermore, sometimes a big flood turns out to be above the amount of flood that was provided for, and the gaging equipment goes with the rest of the flood damage. In such a situation, if the quantity can be ascertained at all, it must be by some other method.

In many cases the highest measurements on the rating curve are at some distance below the actual crest. In such cases the flood quantities must be obtained by extrapolation. Extrapolation is always more or less uncertain, and estimates based on it will be considerably less accurate than those of flows that come within the maximum quantity actually measured.

A certain number of the flood flow records were obtained under more favorable conditions. At Lawrence, Mass., the Merrimack River flows over a water-tight granite dam thirty feet high. The flashboards that somewhat obstruct smaller flows are all gone before a maximum flood occurs. The water drawn through the canals and wheels of the mills is known or can be estimated with a degree of accuracy quite sufficient for the purpose. If the dam were lower there would be a question of backwater

[3] Hoyt-Grover, "River Discharge," John Wiley & Son, 1907, p. 64.

against it in extreme floods, but this is not an element at Lawrence.

Similar conditions of accurate measurement of flood flows are found on the Hudson River at Mechanicville, the Passaic River at Great Falls, the Little River of the municipal water supply of Springfield, Mass., and in other cases.

Records from such gaging stations might well be given a higher rating and might be separated for special study as a safer guide in establishing the basic ratios of flood flows; and this has been tried to some extent. It is creditable, however, to the Geological Survey records that the results obtained in these cases check very well with those obtained from all the data.

Notwithstanding this satisfactory check, we must consider that many of the records available and used do not represent a high degree of accuracy.

Quantities usually bear more or less definite relations to gage heights, and the two forms of expressing flood flows are convertible. Gage heights are more important to the public than quantities. That is to say, the country that is flooded and the damage that is done are more tied up with the water elevation than with the water quantity.

An error in the rating curve at the top may thus affect figures in our tables and the ratios between the different kinds of floods. It does not follow that there will be similar relative errors in the estimates of the height to which water may be expected to rise.

If the records of flow of gaging stations regularly maintained frequently fall short of desirable accuracy, what is to be said of the estimates of flood flows on streams that are not regularly gaged, and especially of estimates made years ago when much less was known of hydraulic flow and when there were few trained hydraulic engineers?

To mention only a few of the errors that we can imagine, take the case of a dam of moderate height that is completely or largely submerged by a great flood, but the flow, nevertheless, is estimated by the weir formula with or without some modifications. Certainly the conditions would result in an estimate of flow greatly in excess of the truth. Such flooding out of dams of moderate height in great floods is common. If one could see the whole situation at the peak of the flood, one could per-

haps know what was happening; but the peak may have come in the middle of the night, no one may have seen it, or, if seen, the observer may not have noted what was most important. The man who makes the estimate long afterward learned as much as he could but not all of the facts.

On the other hand, dams that are filled with sediment almost to their crests will have great velocities of approach and may discharge much more than would be computed by the formulas likely to have been used years ago.

It is not surprising that Mr. Matthes, speaking of a reexamination of published records of notable floods in Pennsylvania for the State Water Supply Commission, stated that there was reason to believe that half of such records were seriously in error.[4]

Methods of hydraulic computation, however, are improving. Increasing use of water resources for power, irrigation, and water supply, as well as greater unit values of water, tend to encourage accuracy of measurement. The structures built in developing water for use often afford facilities for more accurate determinations of quantity than had previously existed.

When this study of flood flows is repeated after the lapse of some years, more and better data will be available. In the meantime the data that we have work out fairly well. We must not be surprised if there are some inaccurate figures, especially in the old records, nor must we be unduly disturbed if here and there is a bit of evidence contradictory to the general trend.

A few of the most important data now used and not readily available elsewhere are shown in the accompanying tables:

[4] Gerard H. Matthes, Transactions Am. Soc. C. E., Vol. 81 (1917), p. 1280.

MERRIMACK RIVER AT LAWRENCE, MASS.
Greatest Daily Flow for 24 Hours in Each Year

Year	Date	Quantity, cfs.	Year	Date	Quantity cfs.
1846	Mar 15	71,250	1887	Apr. 13	40,700
1847	Apr. 25	42,000	1888	May 1	38,800
1848	May 5	32,400	1889	Nov. 30	23,800
1849	Nov. 11	56,850	1890	Oct. 21	31,450
1850	May 1	62,400	1891	Mar. 25	41,200
1851	Feb. 18	36,300	1892	May 24	24,800
1852	Apr. 23	94,800	1893	May 6	44,800
1853	Feb. 8	53,400	1894	Mar. 9	27,900
1854	May 2	60,510	1895	Apr. 16	65,300
1855	Apr. 21	52,900	1896	Mar. 3	82,150
1856	Apr. 11	34,650	1897	July 16	41,499
1857	Apr. 16	56,620	1898	Mar. 15	36,000
1858	Sept. 18	35,250	1899	Apr. 17	38,200
1859	Mar. 20	73,300	1900	Feb. 15	52,989
1860	Mar. 5	25,900	1901	Apr. 9	62,511
1861	Apr. 16	50,600	1902	Mar. 4	61,185
1862	Apr. 21	70,790	1903	Mar. 13	45,469
1863	Apr. 20	54,850	1904	May 1	46,336
1864	Mar. 8	63,500	1905	Mar. 30	45,940
1865	Mar. 18	63,500	1906	Apr. 17	35,400
1866	Feb. 26	34,220	1907	Nov. 8	32,330
1867	Apr. 18	43,680	1908	Feb. 17	22,895
1868	May 25	49,500	1909	Apr. 17	34,929
1869	Oct. 6	70,790	1910	Mar. 3	28,420
1870	Apr. 21	89,780	1911	Mar. 31	20,918
1871	Mar. 14	34,780	1912	Apr. 9	30,720
1872	Apr. 12	46,370	1913	Mar. 29	37,040
1873	Apr. 12	44,140	1914	Apr. 22	37,144
1874	Jan. 10	53,380	1915	Feb. 27	39,200
1875	Apr. 6	54,310	1916	May 19	32,883
1876	Mar. 30	52,530	1917	Mar. 29	31,116
1877	Mar. 29	66,570	1918	Apr. 4	26,928
1878	Dec. 12	76,300	1919	Mar. 30	38,270
1879	May 2	36,800	1920	Mar. 29	51,611
1880	Apr. 6	27,690	1921	Mar. 11	23,398
1881	Mar. 12	29,420	1922	Apr. 13	42,913
1882	Mar. 4	35,030	1923	May 1	55,107
1883	Apr. 15	30,500	1924	Apr. 9	47,669
1884	Mar. 29	46,600	1925	Mar. 31	49,737
1885	Nov. 11	24,720	1926	Apr. 27	33,675
1886	Feb. 15	46,100	1927	Nov. 6	66,625

Average for 82 years, 45,853

Essex Company office, January 23, 1920.

Note.—The results for the last eight years, also computed by R. A. Hale, were subsequently communicated and added to this table.

Connecticut River at (Holyoke) Sunderland, Mass.

Catchment Area, 8000 Sq. Mi.

Year	0	1	2	3	4	5	6	7	8	9
1880	44,100	49,050	45,000	68,300	71,900	63,950	80,150	85,500	99,750	37,650
1890	46,750	67,300	63,100	94,350	43,300	115,000	112,050	75,350	76,150	82,500
1900	.....	.....	.....	.....	69,300	93,300	76,300	71,000	63,700	95,400
1910	85,800	58,900	82,500	107,000	88,300	70,200	72,600	59,700	68,500	78,000
1920	89,500	74,300	103,000	83,700	59,700	97,400	92,400	165,000		

Connecticut River at Hartford, Conn.

Catchment Area, 10,234 Sq. Mi.

1840	.....	.....	.....	175,000	97,000	93,000	90,000	110,000	68,000	81,000
1850	107,000	61,000	130,000	106,000	205,000	64,000	132,000	97,000	48,000	166,000
1860	71,000	115,000	192,000	64,000	79,000	147,000	106,000	101,000	115,000	167,000
1870	154,000	89,000	99,000	109,000	137,000	90,000	121,000	130,000	142,000	116,000
1880	66,000	75,000	64,000	108,000	121,000	88,000	119,000	127,000	98,000	70,000
1890	73,000	102,000	.....	143,000	59,000	161,000	170,000	111,000	114,000	122,000
1900	136,000	169,000	159,000	135,000	97,000	143,000	102,000	110,000	88,000	150,000
1910	99,000	65,000	108,000	165,000	117,000	106,000	108,000	86,000	90,000	99,000
1920	124,000	100,000	150,000	120,000	107,000	105,000	108,000	196,000		

Little River at Westfield, Mass.

Catchment Area, 48½ Sq. Mi.

1900	.....	.....	.....	.....	.....	.....	1,179	1,779	990	1,547
1910	1,242	1,280	1,304	1,119	1,490	1,844	863	877	641	1,468
1920	1,939	953	918	1,357	2,988	1,427	719	3,794	1,512	

Passaic River at Great Falls, Paterson, N. J.

Catchment Area, 785 Sq. Mi.

1890	.....	.....	.....	.....	.....	.....	.....	.....	9,504	7,827
1900	9,429	10,494	21,368	27,995	9,091	8,755	5,809	9,187	7,156	6,486
1910	8,979	4,028	10,424	7,447	7,985	7,803	6,129	4,527	6,486	8,627
1920	11,605	6,244	6,563	7,675	10,787	6,036	5,519	8,707	4,396	

Tohicken Creek at Point Pleasant, Pa.

Catchment Area, 102 Sq. Mi.

1880	.....	.....	.....	.....	4,379	3,664	5,359	2,544	3,492	4,714
1890	2,942	2,851	3,158	2,994	8,650	3,857	6,515	3,683	4,160	3,222
1900	4,089	5,959	4,968	4,395	4,174	3,200	4,120	2,770	3,050	3,369
1910	2,520	3,800	2,470							

Perkiomen Creek Near Frederick, Pa.

Catchment Area, 152 Sq. Mi.

1880	.....	.....	.....	.....	.....	3,192	4,395	4,099	5,305	5,567
1890	7,051	4,803	3,769	5,139	8,769	4,203	6,789	4,747	5,552	4,043
1900	3,606	6,017	6,843	6,181	5,460	5,708	4,050	4,850	5,570	3,370
1910	4,590	2,130	4,670	4,950						

Neshaminy Creek below the Forks, Pa.

Catchment Area, 138 Sq. Mi.

Year	0	1	2	3	4	5	6	7	8	9
1880	.....	.....	.....	.....	.....	4,484	5,767	3,159	4,890	3,528
1890	2,990	5,218	3,589	3,154	9,012	3,234	8,707	4,677	5,076	3,687
1900	3,990	4,624	6,063	6,985	4,696	4,064	3,050	4,630	2,720	3,760
1910	3,539	4,073	3,490							

Des Moines River at Des Moines, Ia.

Catchment Area, 6462 Sq. Mi.

1890	.....	.....	.....	.....	.....	.....	.....	27,700	9,500	11,500
1900	6,100	12,300	40,000	49,000	9,900	13,200	15,500	17,000	22,500	21,600
1910	15,000	6,000	29,700	14,000	8,900	26,000	12,500			

Colorado River at Austin, Tex.

Catchment Area, 34,200 Sq. Mi.

1890	.....	.....	.....	.....	.....	.....	.....	.....	30,200	91,800
1900	145,000	28,700	31,250	33,070	46,140	51,190	70,300	28,100	72,600	29,700
1910	27,400	.....	.....	.....	.....	84,000	28,200	7,840	64,400	64,700
1920	28,100	50,200	103,000	47,500						

Columbia River at The Dalles, Ore.

Catchment Area, 237,000 Sq. Mi.

1850	.....	.....	.....	.....	.....	.....	.....	.....	563,000	874,000
1860	668,000	618,000	948,000	777,000	654,000	714,000	839,000	671,000	483,000	328,000
1870	777,000	856,000	737,000	638,000	582,000	684,000	958,000	486,000	.....	643,000
1880	914,000	598,000	883,000	.....	698,000	482,000	673,000	896,000	564,000	302,000
1890	633,000	448,000	607,000	679,000	1160,000	475,000	785,000	780,000	649,000	787,000
1900	536,000	662,000	644,000	787,000	629,000	412,000	374,000	587,000	653,000	675,000
1910	566,000	574,000	568,000	759,000	493,000	328,000	727,000	727,000	578,000	553,000
1920	428,000	773,000	677,000	581,000						

Alameda Creek at Sunol, Calif.

Catchment Area, 620 Sq. Mi., for Record Year Beginning July 1

1880	.....	.....	.....	.....	.....	.....	.....	.....	.....	22,189
1890	9,215	4,082	16,206	16,741	10,854	6,356	8,395	497	8,395	8,395
1900	8,256	4,131	6,679	2,343	1,883	7,029	10,882	1,173	10,620	2,341
1910	14,745	808	918	8,202	6,684	6,715	7,106			

CHAPTER V

THE COEFFICIENT OF FLOOD

The average annual flood, or as we may call it, the mean flood, is the best available index of the flood-producing capacity of different catchment areas. The average value is preferably determined from a record covering a considerable number of years. Long records are best, but short records of ten or even five years may give an approximate notion that will be helpful in the lack of better data. Flood quantities seem to fluctuate in cycles or pulses, so that a short record may give an indication that differs considerably from a longer one.

Factors Affecting Coefficient.—The mean flood may be expressed in cubic feet per second per square mile, following a common custom, but this procedure is open to the objection that floods do not increase in proportion to the size of the catchment areas from which they come; and, other things being equal, the mean flood expressed as cubic feet per second per square mile is proportionally smaller for large areas than for small ones.

An improvement in this form of expression may be made by using, as a basis for comparison, a fractional power of the catchment area instead of the area itself. If we knew exactly what exponent would best fit all the data, it could be used to great advantage. It is not to be expected that any exponent can be ascertained that will apply exactly in all cases, because different climates and different physical conditions will lead to variation in this respect.

The element of time also enters to some extent. If extreme peak floods are considered, or even the maximum rate of flow for an hour, the exponent will be smaller. If average one-day floods are used, as we are now doing, the exponent will be materially greater. For ten-day flows, it would be still higher.

Weston E. Fuller examined the relation of mean flood to

size of catchment area in his paper on Flood Flows.[1] He divided the data available to him into five geographical parts, and made a separate diagram for each. One of Fuller's diagrams has been brought up to date, namely, the one for the Atlan-

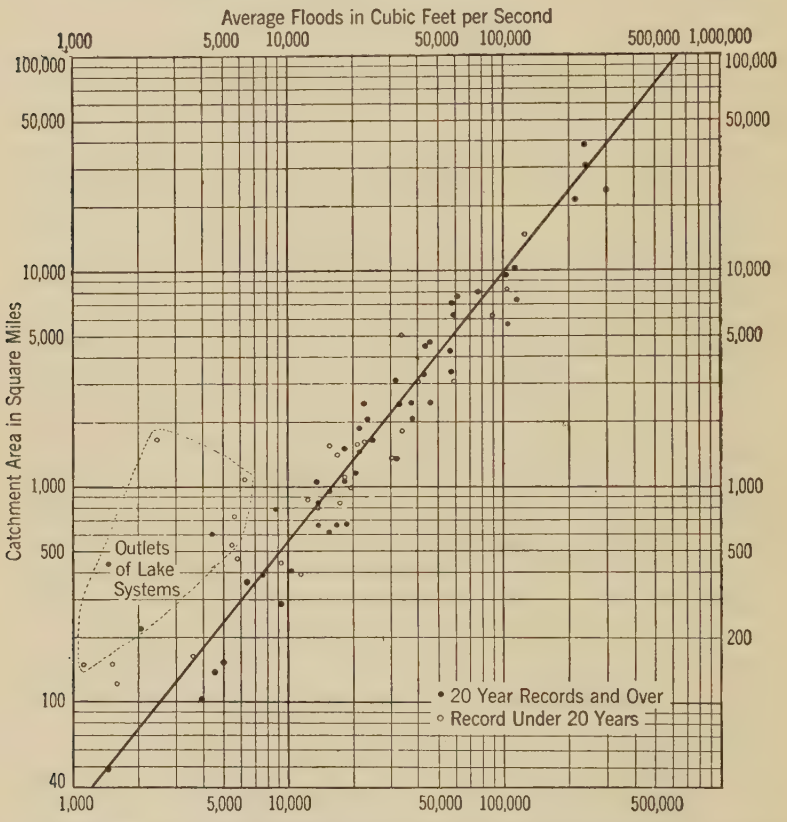

FIG. 2.—Relation of Flood Magnitudes to Sizes of Catchment Areas. Atlantic Coast Streams both North and South, Including Records in Groups I and II, the Boundaries of which are Shown in Fig. 37.

tic states, both north and south, and is presented in Fig. 2. This shows all average one-day flood records as listed for Groups 1 and 2, Parts I and II, of the table in Chapter IX. In this plotting, the records twenty years and over from Part I have

[1] Transactions Am. Soc. C. E., Vol. 77 (1914), p. 564.

been shown by full black circles, and shorter records from Part II by open circles.

It is seen from the figures that a number of points for small areas show coefficients that are out of line with, and considerably lower than, the others. All these are found to represent streams that are outlets of lakes or that are mainly fed by lakes. The smallness of the coefficients for these streams is attributed to this lake storage, which distributes the flood flows over a longer period of time and reduces the one-day floods and the coefficients. The points showing the coefficients for the streams to which this applies are indicated upon the diagram.

No doubt there are other records that represent streams on which similar conditions exist, but in less marked degree. A more rigorous study might lead to the exclusion of a few additional records.

On this diagram has been drawn a single black line at the inclination which corresponds to the 0.8 power of the catchment area. With the exception of a few records representing lake outlets and streams with very great storage, this line follows the inclination indicated by the data. The value of the exponent for this eastern area found by Mr. Fuller in his study is therefore confirmed. Numerous data during the seventeen years since his work do not change the indicated value of the exponent.

Dividing the mean flood by the 0.8 power of the catchment area gives us the *coefficient of flood.*

$$\textit{Coefficient of flood} = \frac{\textit{Mean flood}}{A^{0.8}}$$

Mr. Fuller made an analysis of the data that he had for four other geographical groups which may be referred to, but for no other group are there as numerous and good data. No attempt will now be made to revise these other groups and bring them up to date. It is to be hoped, however, that the matter will be taken up from time to time. This is most likely to be done in connection with the intensive study of local data in their application to some important engineering problem at a time when that problem arises. This is happening all the time in different parts of the country; and instead of trying to generalize now on meagre data, the opportunity and need of further study of local conditions are pointed out.

In the interior where the climate is arid, the extent of snow-capped mountain peaks has more to do with the size of flood flows than has the total catchment area. Flood flows on such streams may easily be greater where streams leave the mountains than at lower points. In such cases flood flows actually become less with greater catchment. There is no merit in using the 0.8 power of the area for such conditions. Otherwise exponents applicable to local conditions probably do not differ widely from the value found for the eastern group. In the present study the same procedure and the same exponent are, for uniformity, used in all cases.

The flood coefficients for records with lengths of twenty years and over will be shown in Part I of the table in Chapter IX. These are plotted upon a small scale map of the United States in Fig. 3. The second part of the same table shows coefficients found from records ranging from thirteen to nineteen years, and these are also shown upon the map. Figure 3 thus gives a general notion of the flood producing capacities of catchment areas in all parts of the United States.

In using it, it must be remembered that there are innumerable local variations that are not, and cannot be, represented on a small general map; and that, in estimating for a particular case, all local data and local differences caused by climate and topography may well be taken into account.

Value of the Exponent.—The value 0.8 for the exponent of area is selected simply because it agrees best with the data for the Atlantic coast both north and south. By way of partial explanation of why this exponent is 0.8 and not 1.0, it will be shown in Chapter XV that intense rainfalls are local in character and that, other things being equal, the average intensity of rainfall is less as the area is greater. The best data available which are examined in Chapter XV, indicate that, between the limits of 500 to 6,000 square miles, the average intensity of rainfall varies with the 0.87 power of the area. This may be accepted as a rough approximation.

It is also to be noted that with larger areas it takes longer for the water from the extremities to reach the gaging stations, and there is less concentration of flow at any one time.

There are undoubtedly other elements, but these two, the decreasing average intensity of rainfall and the greater disper-

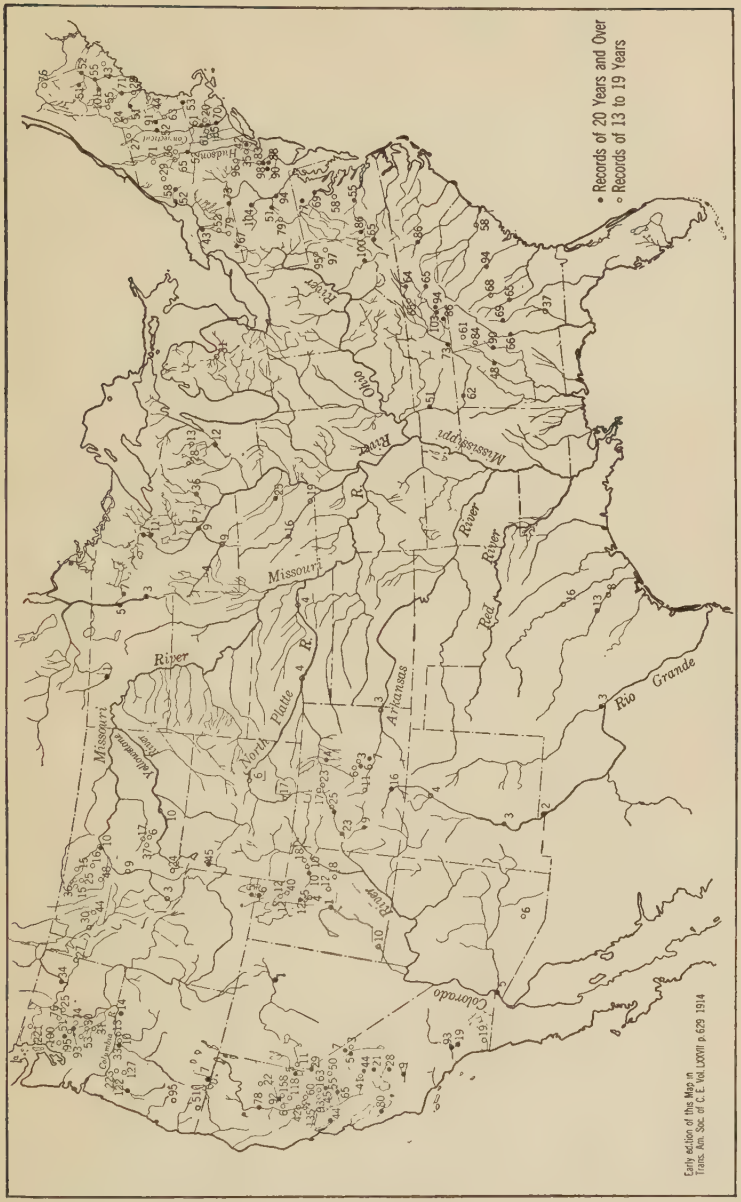
• Records of 20 Years and Over
◦ Records of 13 to 19 Years
Missouri River
Mississippi River
Red River
Arkansas River
Rio Grande
Colorado River
North Platte R.
Yellowstone River
Early action of this Map in Trans. Am. Soc. of C. E. Vol. LXXVII p. 629 1914

FIG. 3.—Flood Coefficients Plotted on Map of the United States.

sion, in point of time, of the flow from larger areas, may be taken as sufficient explanation for the exponent 0.8 and of the fact that flood flows do not increase in proportion to catchment areas.

If we were dealing with extreme maximum rates of flow instead of one-day average rates, it would be found that the exponent would be considerably smaller than 0.8, and a value of 0.7 would more nearly account for observed variations.

Methods of Calculating the 0.8 Power.—There used to be a preference for exponents that could be expressed in even terms because of the convenience of calculation, but with modern methods of calculation the objection to fractional exponents has disappeared. The 0.8 power of catchment areas may be calculated by logarithms to secure precise results. As a practical matter, however, values may be calculated with an ordinary log. log. slide rule with sufficient accuracy for most purposes.

For areas up to 200 or 300 square miles the log. log. rule will give results of desired accuracy with a single setting. For larger catchment areas, owing to the shortening of the log. log. scale for large numbers, it will be more accurate to take the 0.8 power of 1 per cent of the area and multiply the result by $100^{0.8}$ or 39.8.

Another method, easily remembered and sufficiently accurate, is to divide the area by the 0.2 power of the area. This is more accurate than taking the value direct because the 0.2 power is read on the log. log. slide rule more accurately than the 0.8 power. Other short-cut methods will easily be found and can be applied for any fractional exponent that may be desired.

Value of Flood Coefficients.—Values of flood coefficients may be said to be dependent upon three factors:

1. Climate
2. Character of the catchment area
3. Storage in lakes, reservoirs, and on meadows.

Under climate may be considered the total average annual rainfall and the distribution of the rainfall seasonally, but the relative severity of the greatest storms is most important. Temperature and dryness of the air are also important, because they affect evaporation and evaporation plays an important part in

disposing of rainfall. Temperature that melts snow is an element in many floods in the north and in streams from high mountains everywhere.

With respect to the character of the catchment area, impervious soil, steep slopes, and compact arrangement of the streams permitting rapid delivery of flood waters resulting from storm flows are elements that tend to increase the value of the coefficient.

A general notion of the coefficient applicable to a particular place may be obtained in some cases by considering known coefficients of other streams in the neighborhood, and especially of streams having characteristics of catchment area, etc., sufficiently similar to make them suitable for a basis of comparison. Such data are shown in Fig. 3 and in the tables in Chapter IX, and these may well be first inspected for such data as they are capable of furnishing for this use.

The next step will be to get additional local data, and such data will frequently be found to cover many points not shown by the map and tables now presented. It will also be well to look for more recent data and to bring the records of all stations up to date so far as is possible.

Storage must be considered as it is or as it is proposed to be. There is no general rule. It will usually be best to base estimates on local data whenever available even though they seem scanty and inadequate. If the data are few and if there is doubt as to their accuracy, they may still be used, but a factor of safety may well be applied to the result deduced from them.

Often it is necessary to make an estimate for a stream when there are no records at all and when there is no possibility of getting a record within a permissible time interval. In such cases an estimate must be based on records of other streams as similar as can be found to the one for which the estimate is to be made.

For the eastern states all the way from Maine to Georgia, and including both slopes of the Allegheny Mountains, a coefficient of 100 may be taken as the ordinary upper limit; and this value, in the absence of other data, should very generally be used for mountainous and hilly areas where there is no important storage. Where there are flatter areas with more sandy

soil and with storage in lakes or reservoirs or meadows flooded by high water, estimates may be reduced somewhat but rarely below 50. Only a few coefficients below 50 are found among our records, and all of these are from streams where there is much storage in reservoirs or natural lakes to equalize the flow. Estimates will frequently be required for streams where such conditions exist and lower coefficients must then be used.

In other parts of the country the data are relatively fewer and more scattered, and the conditions in general are not as homogeneous, if that term may be used, as they are in the eastern states. The same methods of looking for, arranging, and sifting local data must be used, and it may be found that a stream farther away may sometimes be a better basis of comparison than one close at hand. Similar conditions of the catchment areas may be more important than proximity. Comparisons of different streams are difficult at best, and only rough approximations must be expected when coefficients are estimated from such data.

CHAPTER VI

THE COEFFICIENT OF VARIATION

The *coefficient of variation* is an index of the relative amount of variation from the mean in any series of figures. The method of calculation is well established and easily carried out so that the results obtained are most satisfactory.

It will be found as the work proceeds that the coefficient variation is the base to be multiplied by factors to find all the other variations that need to be known or estimated.

The variation of a term in a series is the amount by which it differs from the mean. The *standard variation* is the square root of the sum of the squares of the variations of the terms of a series divided by the number of terms minus one. The mathematical reason for dividing the sum of the squares by one less than the number of terms may be found in Chapter IV of Merriman's "Method of Least Squares" and in other works on statistical methods.

Coefficient of Variation Defined.—The coefficient of variation is the ratio of the standard variation to the mean of the series.

Where the series is expressed in ratios to the mean, the standard variation and the coefficient of variation become the same; otherwise the distinction must be made.

The coefficient of variation of any series of numbers is a measure of the degree of dispersion of those numbers. That is to say, if they are all nearly the same in size, the coefficient of variation is small. If they vary through a wide range, the coefficient is large. An example of the calculation of the coefficient of variation will be presented in the following chapter.

The coefficient of variation is widely used in statistical and probability work, and the method now described is the one that is commonly used and that is most suitable for giving an index of the variability of the numbers.

The coefficients of variation computed from long and short sections of the same series give, on an average, the same results. For instance, if we have a 100-year flood record and divide it into ten parts of 10 years each and calculate the coefficient of variation for the whole series and for the parts, then the average of the ten values for the 10-year periods will be approximately the same as the figure obtained from the 100-year series.

Probable Error.—The probable error or the probable variation is the variation such that half the variations are greater than it. If the dispersions are equally divided up and down, 25 per cent of the terms will normally be greater than the mean plus the probable variation, and 25 per cent will be smaller than the mean less the probable variation. The remaining 50 per cent will be between the limits.

The probable error is 0.6745 of the standard variation. The probable error or variation is used as a basis for many statements and tabulations. It bears a constant ratio to the standard variation, and since the standard variation is reached first in calculation, it is simpler to use the standard variation as a basis for subsequent procedure, and leave the probable variation out of the program. This reduces by one the number of operations without any decrease in accuracy.

To help in finding the place, so to speak, in the tables given in the textbooks, and to make sure of the decimal points, the accompanying short table is given for a normal series.

The terms in columns I and II are the ones most likely to be found in the textbooks, whereas those in columns III and IV are the ones which will be needed in our present work. One is easily obtained from the other when the key is understood. A more extended table of the values in columns III and IV is presented in Table I of the Appendix.

The use of these values in columns III and IV may be made apparent by an example.

Suppose that the mean flood of a stream is 10,000 cfs. and that the standard variation is 4,000 cfs. The coefficient of variation will then be 0.40. If the series follows the normal law of error, there will be 1 per cent chance of a flood greater than the mean flood, by 2.326 times the standard variation: that is, $10{,}000 + [2.326 \times 4{,}000] = 19{,}300$ cfs.

Similar estimates may be made for floods of any other desired degrees of rarity for which the table furnishes values.

TABLE OF VALUES IN SERIES FOLLOWING THE NORMAL LAW OF ERROR

I Terms within limits as usually given in mathematical tables	II Variation in terms of probable error for a normal series	III Terms beyond limit at one end only as ordinarily required in flood flow calculations	IV Variation in terms of standard variation for a normal series
0	0	50	0
20	0.375	40	0.253
40	0.777	30	0.524
50	1.000	25	0.6745
60	1.248	20	0.842
70	1.536	15	1.036
80	1.901	10	1.282
90	2.439	5	1.645
96	3.045	2	2.054
98	3.448	1	2.326
99.8	4.581	0.1	3.090
99.98	5.512	0.01	3.718

If the series of flood flow quantities follows the normal law of error—that is to say, if the variations from the average upward and downward are equal in number and equal in magnitude, one can compute by this method the probability of the occurrence of a flood above any limit, using the factors in the foregoing table and the intermediate values that may be found in a full table.

This simple procedure does not lead to results that may be accepted because the curve representing flood flows, instead of being normal, is a skew curve. The variations upward are greater in magnitude and smaller in number than the variations downward. This characteristic of the flood-flow curves is persistent and must be recognized. The method to be used in dealing with it will be taken up in the next chapter.

CHAPTER VII

THE COEFFICIENT OF SKEW

Data relating to flood flows diverge systematically from the normal law of error and are of the kind referred to as producing skew curves. Normal curves have equal sides. In other words, they are symmetrical. Skew curves have unequal sides, and are not symmetrical. It is found that practically all stream-flow data form skew curves. Among the characteristics of such curves are these: more than half the terms are below the mean, and the greatest term exceeds the mean by a larger amount than the smallest term falls short of it.

Skew Curves.—The whole subject of flood-flow quantities may fairly be said to be a study in skew curves. Data are said to follow a skew curve when they follow or approximate a law of probability but not the normal law.

Skew curves have been studied mathematically for many years and much may be learned of them in textbooks of statistics and probability. The earlier mathematical methods used in investigating skew curves have been rather difficult.

Skew curves may be handled graphically. The graphic treatment is important and in some cases is the most satisfactory or even the only way yet available for dealing with these data.

The mathematical processes or rather the means of their application have been treated by H. Alden Foster in his paper on Skew Curves.[1] Mr. Foster has not only perfected these methods but has simplified the application of them so that the matter can be followed to certain and satisfactory results without great difficulty in the mathematical procedure that must be employed.

There are other methods of handling skew curves that are more or less arbitrary; these will be mentioned in subsequent chapters.

[1] Transactions Am. Soc. C. E., Vol. 87 (1924), p. 142.

EXAMPLE OF CALCULATION OF THE COEFFICIENTS OF VARIATION AND SKEW
LITTLE RIVER AT WESTFIELD, MASS.

Catchment Area, 48½ Sq. Mi.

Year	Maximum discharge in million gallons daily	Discharge arranged in order of size	Plotting position	In terms of mean	Difference from 1	Difference squared	Cube of difference	
							+	−
1910	803	2452	2.63	2.599	+1.599	2.560	4.080	
1911	827	1931	7.89	2.047	1.047	1.096	1.140	
1912	843	1253	13.16	1.328	0.328	0.108	0.035	
1913	723	1192	18.42	1.264	0.264	0.070	0.018	
1914	963	977	23.68	1.036	0.036	0.001	0	
1915	1192	963	28.95	1.021	0.021	0	0	
1916	558	949	34.21	1.006	0.006	0	0	
1917	567	922	39.47	0.977	−0.023	0	.....	0
1918	414	877	44.74	0.930	0.070	0.005	.....	0
1919	949	843	50.00	0.894	0.106	0.011	.....	0.001
1920	1253	827	55.26	0.877	0.123	0.013	.....	0.001
1921	616	803	60.53	0.851	0.149	0.022	.....	0.003
1922	593	723	65.79	0.766	0.234	0.055	.....	0.013
1923	877	616	71.05	0.653	0.347	0.120	.....	0.042
1924	1931	593	76.32	0.629	0.371	0.137	.....	0.051
1925	922	567	81.58	0.601	0.399	0.159	.....	0.063
1926	465	558	86.84	0.591	0.409	0.167	.....	0.068
1927	2452	465	92.11	0.493	0.507	0.256	.....	0.130
1928	977	414	97.37	0.439	0.561	0.314	.....	0.176
	Total...	17,925	.....	19.002	.....	5.094	+5.273	−0.548

Average discharge for 19 years 943.4 million gallons daily

$$\text{C.V.} = \sqrt{\frac{5.094}{19 - 1}} = 0.531$$

$$\text{C.S.}_{\text{comp.}} = \frac{5.273 - 0.548}{(19 - 1)0.531^3} = 1.745$$

$$\text{C.S.}_{\text{adj.}} = 1.745 \times \left(1 + \frac{8.5}{19}\right) = 2.530.$$

Coefficient of Skew.—In order to discuss this question, one must have a measure of skew that can be applied to each series

of data. The measure used is the sum of the cubes of the variations of the terms of the series divided by the number of terms less one and the quotient divided by the cube of the standard variation. This value is called the *coefficient of skew.*

Calculation of Coefficient of Skew.—The coefficient of skew may be conveniently calculated at the same time as the coefficient of variation. Two extra columns in the table are required. An example of the calculation of both these coefficients for a representative flood record is given herewith. In the table showing the calculation are added the decimal plotting points determined by the method stated in Chapter III, and the plotting of results is shown in Fig. 4.

The last step in this procedure will be described below.

That the process is not an unduly laborious one is indicated by the fact that the data for this calculation were listed, the calculation of the coefficients of variation and skew was made, and the results were plotted by a skilled man—who had been making these calculations for some time—in one hour and fifteen minutes.

If one wishes to try his hand at the procedure, he can select any one of a dozen records for which values are shown in Chapter IV, list them and carry out the calculations. The correct answers are shown in the table in Chapter IX, so that he can be sure he has it all straight. Plottings will also be found in the same chapter for most of these records.

It may also be further interesting to try drawing normal lines to represent the data, beginning with Fig. 4 and extending the trial to any plottings that may be made, and then to compare the results with the lines drawn by rule represented in Fig. 7 and in the diagrams for the other rivers that follow.

Adjustment of Coefficient of Skew.—Unlike the coefficient of variation, the coefficient of skew does depend upon the number of terms in the series used for computing it. If a 100-year series is divided into ten series of 10 terms each, the average of the coefficients of skew computed for these 10-term series will be considerably less than the value computed for the series as a whole.[2]

To bring all estimates of skew to the same basis, it is necessary to use an adjustment for values obtained by calculation

[2] Transactions Am. Soc. C. E., Vol. 87 (1924), p. 174.

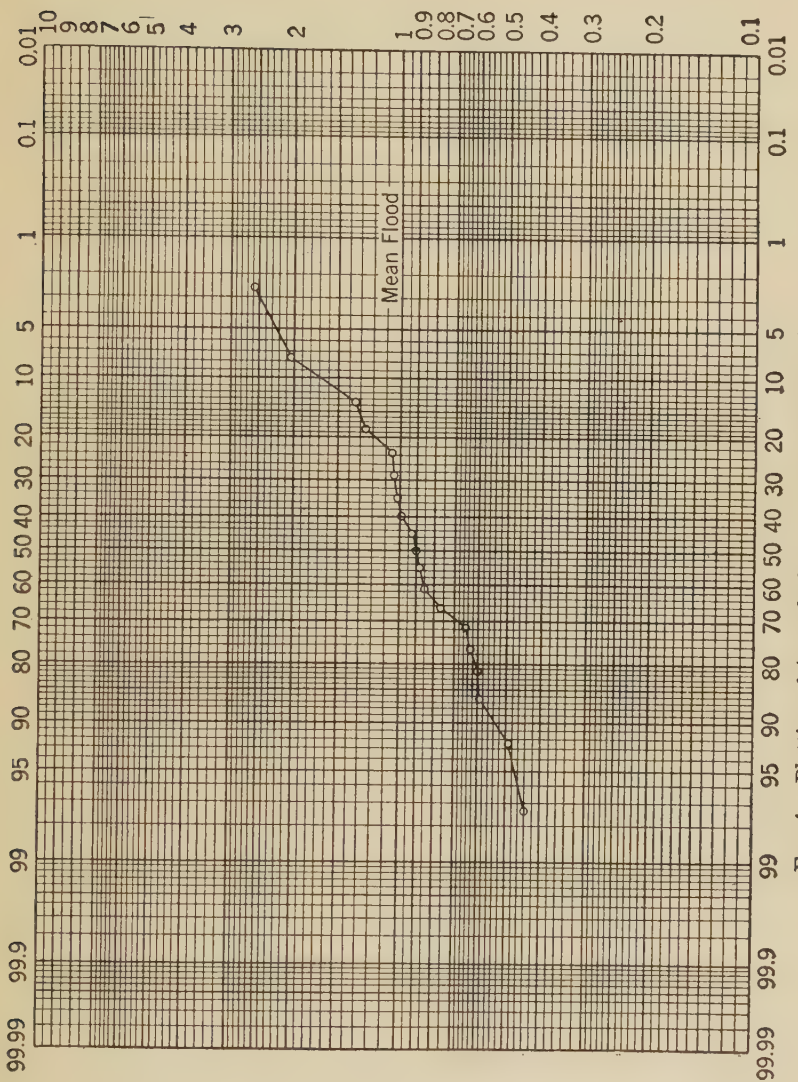

FIG. 4.—Plotting of Annual Floods in Little River 19-year record.

from short-term records. This adjustment is intended to make up for this difference, and, when made, the average of the values for the ten series of 10 years each should be the same as that derived from the 100 terms taken all as one series. The adjustment is made by multiplying the calculated coefficient by a factor whose value depends upon the number of terms.

The value of the factor is found by the formula:

$$F = 1 + \frac{8.5}{n}.$$

For a 25-year term the value of this factor F is 1.34. This means that 34 per cent must be added to the coefficient of skew computed for a 25-term series to obtain the adjusted value. For other periods, varying percentages according to the length of time are added. A table of factors for series of the most common lengths is given as Table V, of the Appendix.

This procedure for adjusting computed results was proposed by the author in discussing Foster's paper. Foster accepted the adjustment as necessary and also the method of making it as above stated, but made a distinction in the method as to which type of curve was to be used. Reference is made to Foster's closing discussion for further details of his suggested procedure.

The adjustment of the coefficient of skew may lead to errors unless due care is used in indicating which results have been subject to this treatment. It is suggested that Foster's proposal shall be followed and that the result first reached shall be designated as the computed coefficient of skew and indicated by the abbreviation $C.S._{comp.}$, and that the value after the factor is applied shall be designated as the adjusted coefficient of skew and indicated by the abbreviation $C.S._{adj.}$. In this study all values are adjusted, and the adjusted coefficient is always stated except in those cases, to be subsequently described, where another procedure is followed, leading to what is called the graphic coefficient of skew.

It may be here pointed out that R. D. Goodrich presented an ingenious method for handling skew curve data by a purely graphic method which does not involve the computation of the coefficient of skew.[3]

[3] Transactions Am. Soc. C. E., Vol. 91 (1927), p. 1.

If the data for one stream only are at hand and to be studied, Goodrich's method of plotting would be satisfactory and perhaps somewhat easier to apply than the method now described. The same may be said of the simple graphic procedure of plotting flood data on logarithmic probability paper and of the duration curve method described in Chapter XII.

But if the records of one hundred rivers are to be compared with each other to find how they vary in skew and how the skews vary with other characteristics such as size of catchment area, geographical location, etc., then we must have a numerical value for the skews in the several cases; and the coefficient of skew as above described is the best basis that has been found for numerical statement.

In one respect Mr. Goodrich's procedure resembles the one that we are following. He adds (or subtracts) a constant to (or from) each term of the series under study, and varies the constant by trial until a value is found that eliminates curvature as far as possible and produces a straight line. Thus is done by a graphic process of trial and error what we are attempting to do by a more direct but possibly no less laborious method.

CHAPTER VIII

DRAWING A SMOOTH CURVE

Data for flood records of 109 American streams have been assembled, arranged, and plotted by the procedure above described. In some of these records the plotting points, representing the annual floods, all come so nearly to a smooth line that there is no difficulty in drawing a line that will accurately represent them.

The old method of smoothing by drawing a curve so that the observation points are about equally divided above and below it for the whole line and for each principal part of it is a dependable method in such cases and leaves little to be desired.

In other cases, especially with short records, the points are more scattered. There is then more difficulty in drawing a smooth line that will fairly represent them all. To help in doing this a procedure has been devised of finding and plotting the skew curve of a series that has the same average value and the same coefficients of variation and skew as are found for the actual data in the record. Certain factors, dependent upon the coefficient of skew, are multiplied by the coefficient of variation; and the products are added to or subtracted from the mean to obtain plotting points for a smooth line.

Use of Factors.—This procedure is an extension of that described in Chapter VI, in connection with the coefficient of variation for plotting curves in accordance with the normal law of error. That procedure is modified by using factors that are graded according to the degree of skew. With zero skew the factors for the normal law of error apply; with small skews factors that differ but little from those that would apply to a normal curve are used; and for the highest skews factors that differ widely from those that apply to normal curves are required.

Factors for use with skew curves were first employed by the

author in connection with the study of storage and spillway problems in California about fifteen years ago. This was when we were beginning to study skew curves and trying to find a satisfactory working method for handling the data to which they applied.

A set of factors was first calculated by the author in spare time on frequent trips to and from California by train. The calculations were afterward checked by assistants and a table of factors was prepared which has since been used, but with additions and corrections growing out of subsequent experience and in one case with a change of base.

The factors calculated in this way were selected so that three criteria would be always met:

Twenty-five terms taken from the curve produced by the use of the factors must have

(1) an arithmetical average equal to the average of the original data
(2) the same coefficient of variation as the original data
(3) the same coefficient of skew as the original data

The use of the factors derived in this way and presented in the Appendix will meet these three conditions within the limits of error.

In addition to meeting the three criteria, the use of these factors in certain cases will result in meeting a fourth one; namely, that:

(4) the plotting points will fall in a straight line on logarithmic probability paper.

That is to say, the logarithms of the twenty-five terms will follow the normal law of error.

A number of artificially prepared series that met this last condition were taken as the starting point for the calculation of the factors. A dozen series were laid out with graded degrees of skew to cover the entire expected range. The factors determined for each one of these series separately were plotted against the computed skews. These in turn were plotted and other values were then taken from the lines for intermediate values required to form the table. This procedure in outline is shown

in Tables VIII, IX and X of the Appendix, and these are arranged to show the basic data that were used in deriving the factors that are used in the present procedure.

Logarithmic Probability Curves.—We may call a series of terms whose logarithms follow the normal law of error a *logarithmic probability series.* One artificially prepared logarithmic probability series is shown in Table VIII of the Appendix.

A logarithmic probability series may be said to bear the same relation to a normal probability series that a geometric progression bears to an arithmetic progression. That is to say, the logarithms of the terms in the geometric progression form an arithmetic progression and the logarithms of the terms in the logarithmic probability series form a series which follows the normal law of error.

Logarithmic probability series can be selected to approach the law of flood flows, as now considered, much more closely than any normal series, but they do not give sufficient flexibility to account for all of the skew curve conditions actually encountered in hydraulic problems.

An investigation was started based on the thought that a natural series could be split into two parts, one of which would follow the logarithmic and the other the arithmetic probability law, and that the combination would account for the actual series. One of the series might theoretically be negative.

This was the starting point but the idea was finally simplified. The following explanation gives a notion of how it was developed.

If we add a constant to, or subtract a constant from, each term of a logarithmic probability series, the results will form a new series that will have the same standard variation and the same coefficient of skew as the original series, but in which the coefficient of variation will be different. It will be changed in the same ratio as the base of the new series is smaller or greater than the base of the original series. Such a series may be called a *modified logarithmic probability series.*

By varying the amounts to be added or subtracted, and with them the coefficients of variation, but without changing the standard variation, it was found that the greatest flexibility could be obtained. Even a normal arithmetic probability series

may be accounted for as a curve of this kind. Such a curve is at one of the limits of the modified logarithmic probability series and may be conceived as having the same standard variation as the actual series, a zero coefficient of variation with an infinite number added, and a zero coefficient of skew. This conception of course has no importance in itself, but it makes clear the fact that any series, however closely it may approach a normal series, may be accurately represented by this procedure.

The idea seems complicated, but in application it proved to be unexpectedly simple. It is unnecessary to go through many of the steps indicated above that are a part of the conception. All the results will be obtained by applying the factors calculated for the logarithmic probability series to the data at hand. One may go through the process of finding the new base and the amount to be added or subtracted and the new coefficient of variation, but this would be done, if at all, as a matter of interest, and not as part of the necessary procedure.

To facilitate this auxiliary procedure in any particular case, there is added to the table of factors, Table II of the Appendix, a column to show a certain coefficient of variation opposite each coefficient of skew. When the coefficient of skew and the coefficient of variation opposite each other are used, the resulting curve will be a logarithmic probability curve. In all other cases the curve produced will be a modified logarithmic probability curve.

By applying the above described factors, each derived from its own series that plots straight on logarithmic probability paper, to other series with the same skew but other coefficients of variation, curves are produced which meet in all cases the above definition of a modified logarithmic probability curve.

All such curves will meet the three criteria above stated. They are found to have a surprising degree of flexibility that permits a fair fit to any series for which this general procedure is suitable.

The logarithmic skew curve factors shown in Table II of the Appendix and used in plotting all the curves shown in this volume were obtained by a procedure based on artificially prepared series of 25 terms each.

This number of terms was selected as fairly representative, in this respect, of the data under examination at the time this

study was started. The exact number, 25, was selected because a series of 25 terms plots on the lines of logarithmic probability paper and no estimating of intermediate positions was required. The plotting points for a 25-term series, following the rule above given, are 2 per cent, 6 per cent, 10 per cent, etc., up to 98 per cent. This statement relates to the first calculation where the values were obtained graphically. Afterward the series were laid out with the aid of a table of logarithms and a calculating machine; when this was done any advantage in the round figures disappeared, but the base first selected was used throughout.

Foster's Factors.—H. Alden Foster in his paper on "Theoretical Treatments of Skew Curves"[1] has computed by a rigorous mathematical procedure the factors to be used in determining plotting points for curves with given coefficients of skew. His calculations cover a considerable additional number of intermediate points and many values for remote limits, and are thus more complete in this respect than the table of factors used by the author for showing logarithmic probability factors. Foster has prepared convenient tables that show the values of these factors, and they are fortunately in form to be comparable with the logarithmic probability factors, and may be used in exactly the same way.

A number of types of skew curves are recognized and the classification of Karl Pierson is commonly followed. Foster made calculations for skew curves of two of these types called Type I and Type III, and tables of values of the factors for these types are presented in Tables III and IV of the Appendix.

Calculations and Plottings.—To show the effect of these factors and to compare the logarithmic probability factor used by the author with those computed by Foster for curves of Types I and III, calculations and plottings have been made of representative data.

In Fig. 5 are shown graphically the computed flood ratios found by using the three sets of skew curve factors for a stream having coefficient of variation of 0.36 and coefficient of skew of 1.4, these being average values for the data in the table for the northeastern section, Group 1, to be described in the following chapter.

[1] Transactions Am. Soc. C. E., Vol. 87 (1924), p. 142.

In Fig. 6 are shown similar data for a stream having a coefficient of variation of 0.76 and coefficient of skew of 1.8, these values being average values for California streams.

Choice of Factors.—Apparently, in choosing a set of factors, the best rule is to use whichever one gives the best fit. Tested in this way, Type III is to be preferred to Type I for flood data in nearly all cases. It is not so easy to choose between logarithmic probability and Type III factors. They are so close together, throughout the range covered by the data, that there is no clean-cut indication of which is best. One fits just as well as the other. The divergences are near the limits and beyond the plotting points of the data.

As a matter of mathematical procedure, the Type III factors, as worked out by Foster would be preferred to the logarithmic probability factors but there is another consideration that may offset this preference.

In considering the whole flood problem there is the remarkable condition that a few very large floods are so high in comparison with all the rest that the question is raised as to whether they belong in the same class or whether they are outside and follow some law of their own which comes into operation only at very long intervals and with extraordinary floods. The author likes to think of these extreme results as belonging to the series and of following the same law. To do this one must endeavor to get all the upward curvature at the upper extremity of the line that the method permits.

Some of these extreme values in two wholly different connections will be mentioned in Chapters X and XIII.

The logarithmic probability factors, other things being equal, will produce higher values for extreme positions. For this reason they are preferred by the author to the Type III factors and are used throughout the present work. It may be assumed that the Foster factors will conform in all cases to the three criteria above mentioned, but not to the fourth one in any event.

There is a difference, however, that must be kept in mind: the logarithmic probability factors were obtained from and applied to a 25-term series, whereas the Foster factors apply to a complete series with an infinite number of terms.

The method of application of these factors will be best explained by an example. For this take the calculation on

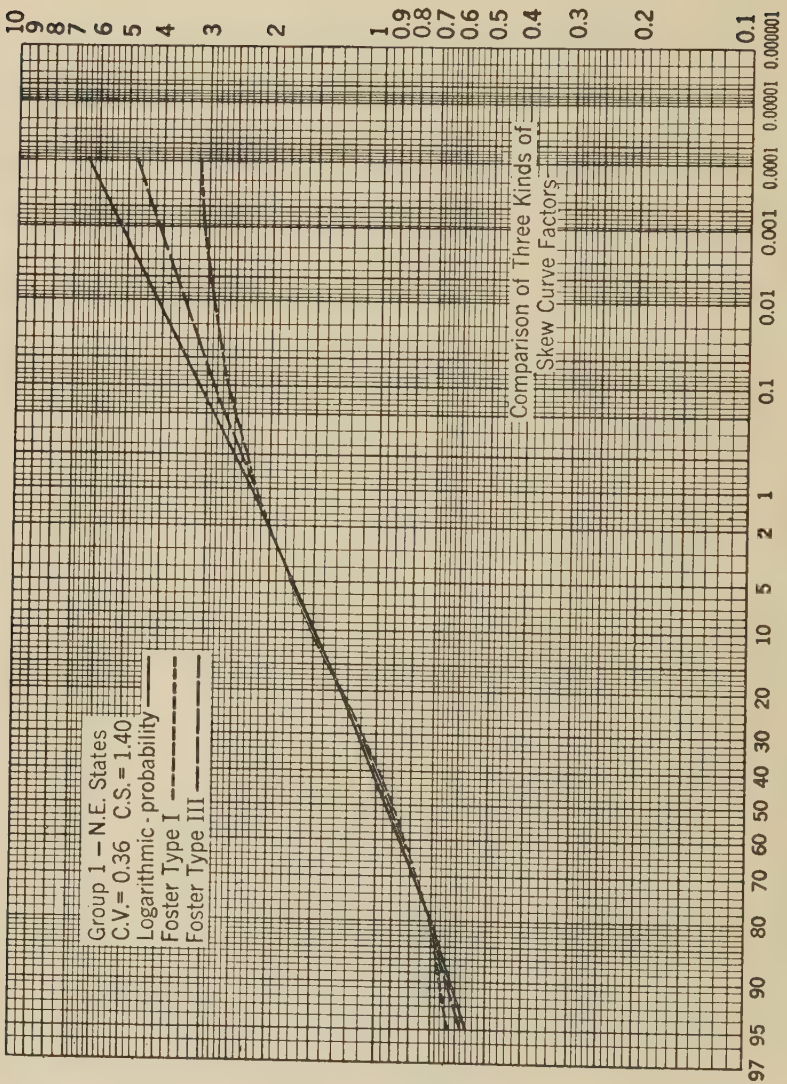
Group 1 — N.E. States
C.V.= 0.36 C.S.= 1.40
Logarithmic - probability
Foster Type I
Foster Type III
Comparison of Three Kinds of Skew Curve Factors
10 9 8 7 6 5 4 3 2 1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1
97 95 90 80 70 60 50 40 30 20 10 5 2 1 0.1 0.01 0.001 0.0001 0.00001 0.000001

FIG. 5.—Illustrating Effect of Using Various Sets of Skew Curve Factors, Eastern Streams.

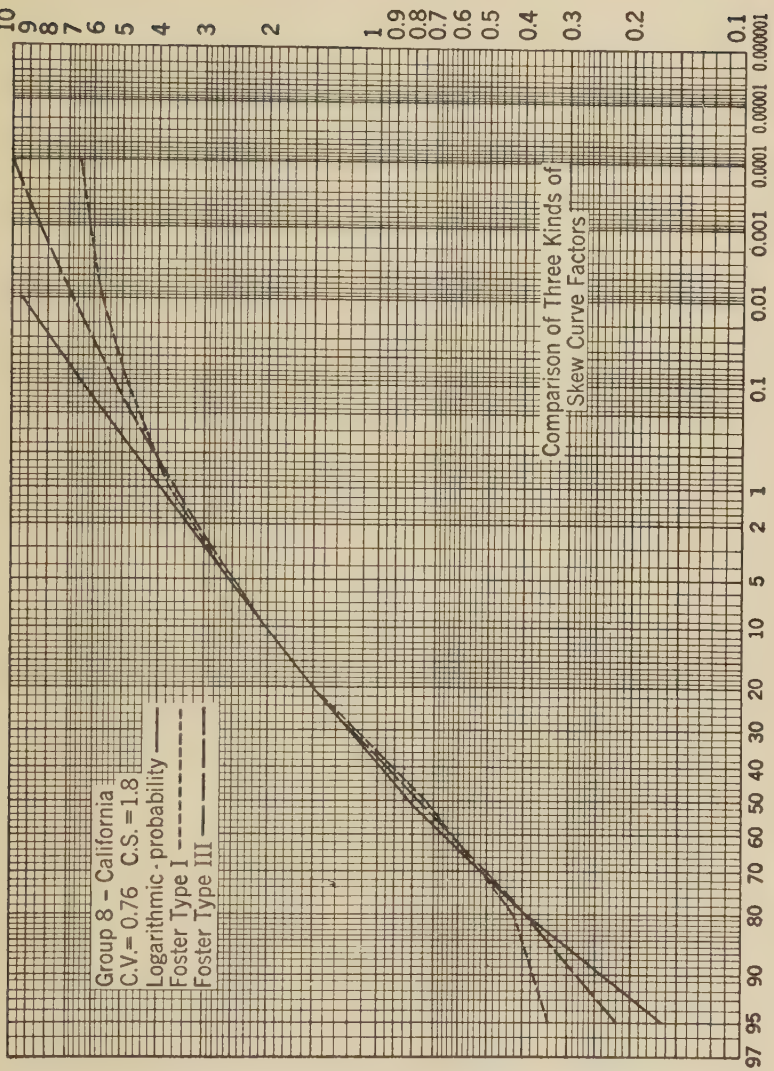

FIG. 6.—Illustrating Effect of Using Various Sets of Skew Curve Factors, California streams

page 43 in Chapter VII. The calculation in tabular form is as follows:

CALCULATION OF PLOTTING POINTS TO DRAW A SMOOTH LINE

Coefficient of Variation, 0.53. Coefficient of Skew, 2.5
Logarithmic Probability Factors used

Plotting point, per cent	Factor from Table II in Appendix corresponding to skew to be multiplied by the C. V.	Product of factor and C. V.	One plus product, being limit in terms of mean flood
99.0	−1.00	−0.53	0.47
95.0	−0.91	−0.48	0.52
80.0	−0.72	−0.38	0.62
50.0	−0.31	−0.16	0.84
20.0	0.51	0.27	1.27
5.0	2.08	1.11	2.11
1.0	4.58	2.43	3.43
0.1	9.75	5.17	6.17

The points so calculated are plotted upon the diagram shown in Fig. 4 and connected by straight lines. The lines so drawn are taken as the smooth line representing the data. The diagram with these additions is reproduced as Fig. 7.

In a great majority of cases the line drawn in this way fits all the data as well as any line that could be drawn.

In Chapter IX are shown plottings made by this method for 29 streams, selected from the entire list of 109 streams that have been plotted. An examination of these diagrams will give an idea of the application of the method and the closeness with which the calculated lines fit the data. The selected diagrams are representative of the entire number, and reproducing all the others would be simply piling up cumulative evidence as to the general shape of the lines and of the application of the method.

Graphic Coefficient of Skews.—In looking at these diagrams it may be remembered that if the coefficient of skew is reduced, it will reduce the size of the terms at both ends and will increase some of the middle terms, the adjustment being such that both

the average of the series and the coefficient of variation will remain unchanged. Increasing the coefficient of skew will have the reverse effect.

On inspecting 109 plottings, 15 were found which, considered in this way, would be better represented by coefficients of skew somewhat different from those reached by the above described method of calculation. The procedure followed when this condition was observed was to make another plotting based on a lower or higher assumed value of the coefficient of skew. In

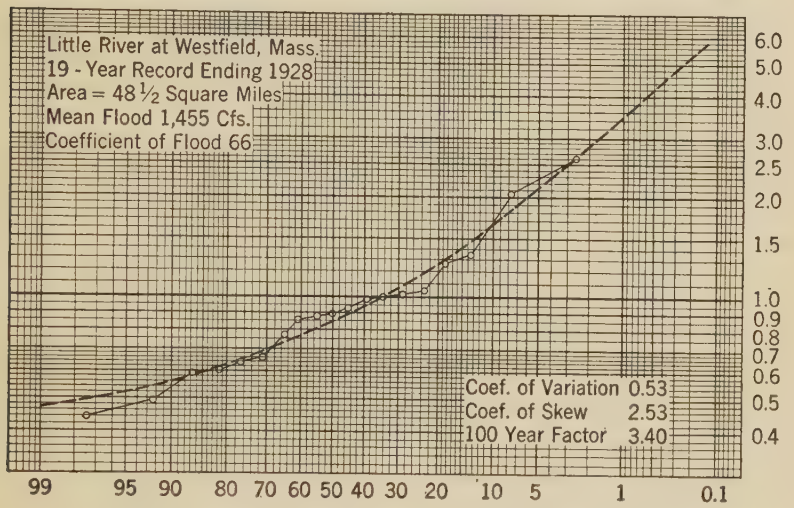

FIG. 7.—Smooth Line as Drawn by the Proposed Method.

other words, in the example shown in Fig. 7 the coefficient of skew is computed to be 2.5. A plotting may be made with a lower coefficient, say 2.2, the procedure being the same in all other respects, and if the new plotting agrees better with the points representing the data, the line so drawn is preferred.

Several such trial lines may be plotted on the original paper in soft pencil, and the one that fits best selected to be inked. This procedure is recommended wherever the conditions warrant it. By following it the line that is drawn and used always fully meets the three criteria mentioned above.

The coefficient of skew used for plotting the line that best represents the data, when it differs from the computed and adjusted value, is called the *graphic coefficient of skew.*

Wherever a graphic coefficient of skew is found that fits the data better, it is substituted for the calculated coefficient of skew in the examples which follow. The graphic procedure is trumps in this game, and no method of calculation stands where the graphic procedure better accounts for the facts.

This procedure of deriving a graphic coefficient of skew is in line with the author's discussion of Foster's paper, where he said:

> The writer thinks that the graphic procedure is still the safest one to follow, and that it furnishes the ultimate test. The use of these factors in drawing smooth curves is helpful and tends toward uniform treatment and accuracy, but it should not be allowed to replace the study of a plotting of the actual data and an endeavor to represent them accurately by a line.
>
> In some cases, the graphic method is the only one that can be used. Rainfalls by days for the whole number of days may be mentioned as an example. In such a series, many of the terms, usually a majority, are zeros. Those that remain might be part of an entire series of which most of the terms were negative. The negative terms are here represented by zeros, and there is no means of dealing mathematically with such a series. In runoff records, similar conditions are found only rarely in streams that remain dry for some of the record periods. A series of terms representing required storage in different years for a given rate of draft present a similar problem. No doubt many other kinds of partial or interrupted series will be found, that can be handled only by graphic methods.[2]

The above described methods of handling skew curves have also been applied to other kinds of data; and they seem to be suited to quite general application and are useful with skew curves from a great variety of sources.

Estimating Floods from Curves.—The average annual flood is the starting point for estimating the floods to be expected in a given stream. This is to be multiplied by factors taken from the curve that correspond to the ten per cent chance, the one per cent chance, or any other desired per cent chance of recurrence in any one year.

The values so found are the values in cubic feet per second for average one day floods that go with the per cent chance to which they correspond.

If estimates are required for the extreme maximum peak rate

[2] Transactions Am. Soc. C. E., Vol. 87 (1924), p. 176.

of flow of other average rates for any time interval, another procedure is required. This will be treated subsequently.

As an illustration, take the Little River ten-year curve. The mean annual flood flow is 943 mgd. or 1455 cfs. We find from the diagram, Fig. 7, that there is a ten per cent chance in any one year of exceeding a limit 1.68 times the mean, or 2440 cfs. This is the estimated ten per cent chance flood.

For a flood of one per cent chance, the factor is 3.43, and the estimated flood is 4980 cfs. The factor for any other desired percentage limit may be ascertained from the diagram and applied to the mean flood in the same way.

The values so reached are the ones that seem most probable as derived from Little River data and nothing else. In other words, if this nineteen-year sample were all that was known about flood flows, the answers as above found are the most probable ones as judged by this procedure.

This does not exhaust the matter, however. We actually have not only this very definite information in regard to Little River flows, but we have a great deal of information as to other streams and their flood flows. All this may well be taken into account before an estimate is made. In other words, we must consider whether this nineteen-year sample of Little River is a representative one, what inferences may be safely drawn from the histories of other streams, and from averages of many streams that may be brought into consideration. If these can be made to contribute to the result, a closer approximation may be reached, and estimates that give due weight to other data will be more reliable and safer.

In this case the indications are, following the procedure to be developed in Chapter X, that more than a fair proportion of great floods entered this particular nineteen-year record, and estimates of rare floods derived from it, without outside control, are probably above the truth.

CHAPTER IX

TABLES AND PLOTTINGS

This chapter is devoted to presenting the available flood data used in the present study. These are shown first in tabular form and afterward, in part, in plottings. The first part of the table shows all of the best flood-flow records available, 109 in number. These have been arranged in accordance with the methods described above, and the coefficients of flood, variation, and skew have been computed and are shown for each record.

Three available records, namely, the Saranac River in New York and the Cobbosseecontee and the Presumpscott Rivers in Maine, have been excluded. Each of these streams is the outlet of a lake system with such storage that the flood coefficient is less than in all the other flood records of streams of its group. It is thought that these records are less useful in indicating normal flood conditions because of the large amount of storage on these rivers, and that averages obtained without including them would be more useful in a general study.

This exclusion has not been extended to numerous other cases where similar conditions exist to a less degree. A further subdivision of data according to the percentages of water surface, or better, according to the ratios of effective storage to mean annual flow, must be left for future study.

Data Presented.—In the table now presented are shown the name of the stream, period covered, catchment area, the coefficients of flood, variation, and skew, and the factor computed to represent the ratio between the mean flood and the one per cent chance flood.

In making up this table the country has been divided into districts, and the records from each district are shown together and averaged. The boundaries of these districts have been drawn with reference to known or supposed flood-flow conditions and without regard to state lines. They do not cover the

whole country, because data are not available to cover it all. The districts are the same as those used in arranging the coefficient of flood data, in Chapter V, and are shown upon a small map of the United States in Fig. 37.

The values stated for the ratio of the one per cent chance flood were computed by the use of the coefficients of variation and skew and the logarithmic probability factors. In fourteen per cent of the cases, where the graphic procedure outlined in Chapter VIII fits the data better, it has been followed. Graphic values are shown only where they differ from computed values and then both values are shown.

The data for each geographic group have been arranged in the order of size of their catchment areas. Where the data were numerous enough to warrant it, they have been averaged in two or three subsections according to size to see whether there were tendencies upward or downward in the coefficients of variation and skew as the catchment area increased. In these cases a general average for the entire group is also shown.

In another study the results from each group, when numerous enough to warrant such classification, were arranged according to the coefficients of variation and were similarly divided and averaged. This study is not here reproduced, but it may be stated in brief that the coefficient of skew does increase with an increase in the coefficient of variation, and on an average tends to be nearly proportional to it.

In several cases a tendency is noted for the coefficient of variation to be smaller as the catchment area is greater. That is to say, large rivers have steadier flows relatively than small ones. This tendency, however, is not clearly marked and is not found in all cases.

The second part of the table shows values of the coefficient of flood for the best of the shorter records, ranging with a few exceptions from fifteen to nineteen years. No calculations of the coefficients of variation and skew have been made for these shorter records.

The third part of the table is a summary of some of the results for geographic groups obtained by averaging the values in the first and second parts of the table for all of the records in that group.

By the use of three coefficients, stated for the 109 streams

in the first part of the table, it is possible, by the procedures indicated, and with the use of the appropriate factors, to make estimates of floods of any degree of rarity for any of these streams.

It will be apparent, as the work proceeds, that some of these records contain more than a fair proportion of high flood flows whereas others contain less, and the conditions in this respect may be inferred in some cases with sufficient definiteness to serve as a basis for a modified and improved procedure, as will be developed in a subsequent chapter.

Taking into account all the data from the streams, it would be possible to make estimates of flood flows for individual streams that would differ from those directly computed from the three coefficients obtained for that particular record, and that would probably be considerably more reliable.

For the present purpose all such adjustments are excluded, the object being to find out, as nearly as possible, what the data from each stream indicate in these particulars without bringing anything else into its own particular record.

Table of Flood Records

Showing base data and values of the coefficients of flood, variation, and skew, and computed ratio of the one per cent chance flood

Part I.—Records 20 Years and Over

GROUP 1

Stream	Place	Number of years in record	Last year in record	Catchment area in sq. mi.	Mean flood, cfs.	Coefficient of				1% chance flood ratio
						Flood	Variation	Skew	Graphic skew	
Susquehanna	Harrisburg, Pa.	31	1921	23,885	299,300	94	0.34	1.2	.....	2.15
*Connecticut	Hartford, Conn.	84	1927	10,234	113,200	70	0.31	0.5	.....	1.85
Potomac	Point of Rocks, Md.	29	1923	9,650	104,300	69	0.41	0.7	.....	2.20
*Connecticut	Sunderland (Holyoke), Conn.	44	1927	8 000	77 900	61	0.30	1.2	.....	1.95
Penobscot	West Enfield, Me.	23	1923	6,600	62,000	55	0.41	2.7	.....	2.90
W. Br. Susquehanna	Williamsport, Pa.	27	1921	5,680	104,400	104	0.32	−0.4	0.0	1.75
Merrimack	Lawrence, Mass.	82	1927	4,663	45,800	53	0.35	0.9	.....	2.07
Hudson	Mechanicville, N. Y.	34	1923	4,500	44,000	52	0.37	3.0	2.2	2.60
Kennebec	Waterville, Me.	32	1923	4,270	57,400	71	0.52	2.1	.....	3.10
	Average of sub-group...	43	.....	8,609	100,922	69	0.37	1.28	.....	2.28
*Juniata	Newport, Pa.	23	1923	3,380	52,666	51	0.42	1.5	.....	2.50
Connecticut	Orford, N. H.	21	1921	3,100	31,960	52	0.22	1.1	.....	1.71
Chemung	Chemung, N. Y.	20	1923	2,440	37,900	73	0.33	0.0	.....	1.77
*Genesee	Rochester, N. Y.	31	1924	2,440	22,600	43	0.38	1.3	.....	2.27
*Androscoggin	Rumford Falls, Me.	30	1923	2,090	23,300	51	0.39	2.2	.....	2.66
Black	Watertown, N. Y.	30	1927	1,878	21,600	52	0.26	1.2	.....	1.87
Allegheny	Red House, N. Y.	21	1924	1,640	24,900	67	0.32	0.3	.....	1.82
Mattawamkeag	Mattawamkeag, Me.	21	1923	1,500	18,300	52	0.39	2.5	1.8	2.51
*E. Br. Penobscot	Grindstone, Me.	20	1923	1,070	13,630	51	0.44	2.8	2.0	2.79
	Average of sub-group...	24	.....	2,171	27,428	55	0.35	1.27	.....	2.21

In averaging coefficient of skews, negative values are taken as 0 and graphic values are used in place of computed values when they differ.
* One or more years missing.

TABLE OF FLOOD RECORDS. PART I.—RECORDS 20 YEARS AND OVER—*continued*

GROUP 1—*continued*

Stream	Place	Number of years in record	Last year in record	Catchment area in sq. mi.	Mean flood, cfs.	Coefficient of				1% chance flood ratio
						Flood	Variation	Skew	Graphic skew	
Passaic	Paterson, N. J.	31	1928	785	8,810	42	0.54	3.4	2.5	3.50
Monocacy	Frederick, Md.	27	1923	660	13,840	77	0.25	0.5	.....	1.60
Pemigewasset	Plymouth, N. H.	39	1924	615	15,500	91	0.30	1.3	.....	2.03
Moose	Moose, N. Y.	26	1927	366	6,463	58	0.33	1.5	.....	2.18
Piscataquis	Foxcroft, Me.	21	1923	286	9,357	101	0.49	1.1	.....	2.58
Perkiomen	Frederick, Pa.	29	1913	152	5,014	90	0.27	0.6	.....	1.76
Neshaminy	The Forks, Pa.	29	1913	138	4,558	88	0.34	1.8	.....	2.30
Tohicken	Point Pleasant, Pa.	29	1913	102	3,968	98	0.34	1.5	.....	2.20
Little River	Westfield, Mass.	22	1927	48	1,443	65	0.51	2.6	.....	3.40
	Average of sub-group...	28	.....	350	7,661	79	0.37	1.49	.....	2.39
	Average of total group..	32	.....	3,710	46,077	68	0.36	1.44	.....	2.29
GROUP 2										
Tennessee	Johnsonville, Tenn.	34	1924	38,500	236,000	51	0.28	0.0	.....	1.65
Tennessee	Florence, Ala.	30	1924	30,800	240,400	62	0.29	1.6	.....	2.07
Tennessee	Chattanooga, Ga.	49	1924	21,400	214,400	73	0.27	1.0	.....	1.85
*Savannah	Augusta, Ga.	39	1925	7,300	114,000	94	0.47	2.2	1.7	2.77
Coosa	Riverside, Ala.	20	1916	7,065	58,000	48	0.23	−0.9	0.0	1.53
James	Cartersville, Va.	24	1924	6,240	59,500	55	0.29	−0.3	.....	1.61
	Average of sub-group...	33	.....	18,551	153,725	64	0.30	0.72	.....	1.91

In averaging coefficient of skews, negative values are taken as 0 and graphic values are used in place of computed values when they differ.

* One or more years missing.

TABLE OF FLOOD RECORDS. PART I.—RECORDS 20 YEARS AND OVER—*continued*

GROUP 2—*continued*

Stream	Place	Number of years in record	Last year in record	Catchment area in sq. mi.	Mean flood cfs.	Coefficient of				1% chance flood ratio
						Flood	Variation	Skew	Graphic skew	
Yadkin	Salisbury, N. C.	29	1924	3,400	58,000	86	0.50	1.0	.....	2.50
*Chattahoochee	West Point, Ga.	27	1924	3,300	43,200	66	0.39	0.8	.....	2.16
*Tallapoosa	Sturdivant, Ala.	23	1924	2,460	46,600	90	0.48	1.5	.....	2.70
Ocmulgee	Macon, Ga.	20	1912	2,420	33,100	65	0.35	0.1	.....	1.92
James	Buchanan, Va.	27	1922	2,080	28,700	86	0.38	−0.2	.....	1.83
Greenbrier	Alderson, W. Va.	29	1924	1,340	32,000	100	0.44	0.4	.....	2.16
Chattahoochee	Norcross, Ga.	20	1923	1,170	20,600	72	0.50	2.2	.....	3.10
	Average of sub-group...	25	.....	2,310	37,457	81	0.43	0.86	.....	2.34
Flint	Woodbury, Ga.	20	1920	1,090	18,500	69	0.45	0.7	.....	2.30
French Broad	Asheville, N. C.	21	1924	949	15,680	65	0.47	0.6	.....	2.33
Holston	Bluff City, Tenn.	23	1924	828	13,780	64	0.44	2.0	1.8	2.70
Little Tennessee	Judson, N. C.	24	1924	675	18,900	103	0.70	2.4	.....	4.10
Tuckasegee	Bryson, N. C.	24	1924	662	16,950	94	0.59	1.1	.....	2.90
*Hiwassee	Murphy, N. C.	23	1924	410	10,570	86	0.49	0.5	.....	2.30
Roanoke	Roanoke, Va.	28	1924	388	7,700	65	0.46	1.0	.....	2.45
	Average of sub-group...	23	.....	714	14,583	78	0.51	1.16	.....	2.73
	Average of total group...	27	.....	6,624	64,329	75	0.42	0.92	.....	2.35

In averaging coefficient of skews, negative values are taken as 0 and graphic values are used in place of computed values when they differ.
* One or more years missing.

TABLE OF FLOOD RECORDS. PART I.—RECORDS 20 YEARS AND OVER—*continued*

GROUP 3

Stream	Place	Number of years in record	Last year in record	Catchment area in sq. mi.	Mean flood, cfs.	Coefficient of				1% chance flood ratio
						Flood	Variation	Skew	Graphic skew	
Mississippi	St. Paul, Minn.	33	1924	35,700	39,500	9	0.50	0.3	.....	2.28
*Red	Grand Forks, N. Dak.	20	1924	25,000	17,400	5	0.53	0.0	.....	2.23
Mouse	Minot, N. Dak.	21	1923	8,400	1,371	1	0.79	1.5	.....	3.82
*Cedar	Cedar Rapids, Iowa.	21	1924	6,640	27,660	25	0.48	1.5	.....	2.70
Des Moines	Des Moines, Iowa.	20	1916	6,462	18,400	16	0.61	1.8	.....	3.37
Red	Fargo, N. Dak.	23	1924	6,420	3,006	3	0.68	0.8	.....	3.02
	Average of sub-group...	23	.....	14,770	16,887	10	0.59	0.98	.....	2.90
Chippewa	Chippewa Falls, Wis.	37	1924	5,600	35,200	36	0.39	0.8	.....	2.16
Red Lake	Crookston, Minn.	23	1924	5,320	6,560	7	0.68	0.7	.....	2.96
Mississippi	Above Sandy, Minn.	20	1915	4.510	5,530	7	0.40	0.6	.....	2.12
Wisconsin	Merril, Wis.	21	1924	2,630	14,900	28	0.34	0.7	.....	2.00
Fox	Berlin, Wis.	27	1924	1,430	3,980	12	0.36	0.5	.....	1.98
Sandy	Below Sandy Lake Res., Minn...	23	1916	424	1,339	11	0.65	1.6	.....	3.35
	Average of sub-group...	25	.....	3,319	11,251	17	0.47	0.82	.....	2.43
	Average of group.....	24	.....	9,045	14,571	13	0.53	0.90	.....	2.66

GROUP 4

*Pecos	Comstock, Texas.	22	1923	48,000	14,760	3	1.01	1.6	.....	4.70
*Rio Grande	El Paso, Texas.	22	1914	40,000	8,770	2	0.70	1.1	.....	3.27
*Colorado	Austin, Texas.	22	1923	34,200	52,900	13	0.61	1.6	.....	3.25
Rio Grande	San Marcial, N. Mex.	27	1921	32,000	12,100	3	0.56	1.6	.....	3.06
	Average of group.....	23	.....	38,550	22,132	5	0.72	1.48	.....	3.57

In averaging coefficient of skews, negative values are taken as 0 and graphic values are used in place of computed values when they differ.

* One or more years missing.

TABLE OF FLOOD RECORDS. PART I.—RECORDS 20 YEARS AND OVER—*continued*

GROUP 5

Stream	Place	Number of years in record	Last year in record	Catchment area in sq. mi.	Mean flood cfs.	Coefficient of				1% chance flood ratio
						Flood	Variation	Skew	Graphic skew	
*Colorado	Yuma, Ariz	21	1923	242,000	107,500	5	0.50	1.1	.....	2.60
*Humbolt	Golconda, Nev	22	1917	10,800	1,322	1	0.67	1.3	.....	3.30
Colorado	Palisades, Colo	22	1923	8,790	32,200	23	0.34	0.5	.....	1.92
Bear Cr	Collinstone, Utah	34	1923	.6,000	6,462	6	0.34	0.6	.....	1.92
*Verde	McDowell, Ariz	20	1923	6,000	28,440	27	0.71	0.4	.....	2.85
*Arkansas	Pueblo, Colo	33	1924	4,600	5,777	7	0.96	5.5	3.2	6.00
Colorado	Glenwood Spring, Colo	23	1923	4,560	21,150	25	0.36	0.4	.....	1.95
Bear	Battle Creek, Idaho	23	1912	4,500	4,546	5	0.41	0.3	0.6	2.15
	Average of sub-group	25	.....	35,906	25,925	12	0.53	1.01	.....	2.84
*Salt	Roosevelt, Ariz	20	1923	4,222	30,880	39	1.13	2.5	.....	6.00
Sevier	Gunnison, Utah	20	1920	3,990	985	1	0.53	1.4	.....	2.81
*Arkansas	Cañon City, Colo	38	1923	3,060	3,840	6	0.33	0.2	.....	1.82
S. Platte	S. Platte, Colo	21	1923	2,610	1,879	4	0.61	3.5	3.0	4.00
*Rio Grande	Del Norte, Colo	20	1913	1,400	5,165	16	0.50	2.8	2.0	3.04
*Uncompahgre	Delta, Colo	20	1923	1,110	1,250	5	0.41	0.4	.....	2.08
Carson	Empire, Nev	22	1922	988	2,655	11	0.42	0.5	.....	2.14
	Average of sub-group	23	.....	2,483	6,665	12	0.56	1.44	.....	3.13
*Provo	Provo, Utah	21	1911	640	2,110	12	0.37	1.7	.....	2.40
Uncompahgre	Montrose, Colo	21	1923	565	1,489	9	0.45	1.6	.....	2.66
Price	Helper, Utah	20	1923	530	1,547	10	0.48	1.1	.....	2.55
Truckee	Tahoe, Calif	23	1923	519	721	5	0.33	1.1	.....	2.07
Owens	Round Valley, Calif	20	1923	450	669	5	0.35	1.0	.....	2.10
W. Br. Carson	Woodsford, Calif	20	1920	70	873	29	0.39	0.6	.....	2.05
Rock Creek	Round Valley, Calif	20	1923	46	147	7	0.49	1.7	.....	2.80
	Average of sub-group	21	.....	403	1,079	11	0.41	1.26	.....	2.38
	Average of group	23	.....	13,975	11,891	12	0.50	1.22	.....	2.78

In averaging coefficient of skews, negative values are taken as 0 and graphic values are used in place of computed values when they differ.

* One or more years missing.

TABLE OF FLOOD RECORDS. PART I.—RECORDS 20 YEARS AND OVER—*continued*

GROUP 6

Stream	Place	Number of years in record	Last year in record	Catchment area in sq. mi.	Mean flood, cfs.	Coefficient of				1% chance flood ratio
						Flood	Variation	Skew	Graphic skew	
Columbia	The Dalles, Ore	64	1923	237,000	653,000	33	0.25	0.3	.....	1.65
*Missouri	Fort Benton, Mont	31	1923	24,600	33,600	10	0.58	2.1	1.5	3.07
*Spokane	Spokane, Wash	31	1924	4,350	25,000	31	0.31	0.1	.....	1.75
Link	Klamath Falls, Ore	20	1923	3,110	4,300	7	0.38	2.2	.....	2.63
	Average of sub-group	36	.....	67,265	178,975	20	0.38	1.02	.....	2.27
Umatilla	Umatilla, Ore	20	1923	2,130	6,422	14	0.51	1.1	.....	2.65
Chelan	Chelan, Wash	21	1924	950	8,110	34	0.21	−0.7	.....	1.39
Snake	Moran, Wyo	20	1923	820	9,710	45	0.24	−0.3	.....	1.51
*St. Mary	Babb, Mont	22	1924	278	3,677	41	0.41	1.2	.....	2.36
	Average of sub-group	21	.....	1,045	6,980	34	0.34	0.58	.....	1.98
	Average of group	29	.....	34,155	92,977	27	0.36	0.80	.....	2.13

GROUP 7

Williamette	Albany, Ore	33	1923	4,860	108,600	122	0.39	0.7	1.0	2.23
Cle Elum	Roslyn, Wash	21	1924	202	6,485	93	0.55	2.4	2.0	3.23
Yakima	Martin, Wash	21	1924	55	2,346	95	0.58	2.2	.....	3.50
	Average of group	25	.....	1,706	39,144	103	0.51	1.73	.....	2.98

In averaging coefficient of skews, negative values are taken as 0 and graphic values are used in place of computed values when they differ.
* One or more years missing.

TABLE OF FLOOD RECORDS. PART I.—RECORDS 20 YEARS AND OVER—*continued*

GROUP 8

Stream	Place	Number of years in record	Last year in record	Catchment area in sq. mi.	Mean flood, cfs.	Coefficient of				1% chance flood ratio
						Flood	Variation	Skew	Graphic skew	
Sacramento	Red Bluff, Calif.	29	1923	9,300	117,200	78	0.49	0.9	.....	2.50
Feather	Oroville, Calif.	22	1923	3,640	65,500	92	0.71	1.2	.....	3.35
*Kern	Bakersfield, Calif.	34	1923	2,345	4,670	9	0.82	3.2	.....	5.20
King	Piedra, Calif.	28	1923	1,740	17,100	44	0.46	2.0	.....	2.87
Tuolomne	Lagrange, Calif.	23	1917	1,500	19,230	55	0.63	2.3	.....	3.70
Yuba	Smartsville, Calif.	20	1923	1,220	35,100	118	0.81	2.1	.....	4.30
	Average of sub-group...	26	.....	3,291	43,133	66	0.65	1.95	.....	3.65
Stanislaus	Knights Ferry, Calif.	20	1923	935	15,600	65	0.88	2.5	.....	5.00
Alameda	Sunol, Calif.	28	1917	620	7,580	44	0.70	1.1	.....	3.26
Keweah	Threerivers, Calif.	21	1923	520	3,177	21	0.76	1.6	.....	3.80
*Tule	Portersville, Calif.	21	1923	266	2,459	28	0.63	0.5	.....	2.70
Arroyo Seco	Soledad, Calif.	22	1923	215	5,930	80	0.85	1.5	.....	4.00
*San Gabriel	Azusa, Calif.	22	1922	214	6,882	93	1.06	2.7	2.0	5.30
Santa Ana	Montone, Calif.	25	1922	182	1,188	19	1.04	2.5	2.0	5.25
	Average of sub-group...	23	.....	422	6,117	50	0.75	1.60	.....	4.19
	Average of group.....	24	.....	1,746	23,201	57	0.76	1.76	.....	3.94

In averaging coefficient of skews, negative values are taken as 0 and graphic values are used in place of computed values when they differ.

* One or more years missing.

Part II.—Shorter Records

Showing Coefficient of Flood Only

GROUP I

Stream	Place	Number of years in record	Last year in record	Catchment area in sq. mi.	Mean flood in cfs.	Coefficient of flood
St. Johns	Van Buren, Me.	16	1923	8,270	103,850	76
Delaware	Riegelsville, N. J.	17	1923	6,190	89,859	83
Delaware	Port Jervis, N. Y.	19	1923	3,070	59,368	96
*Saco	West Buxton, Me.	15	1923	1,550	15,647	44
Merrimack	Franklin Junction, N. H.	20	1923	1,460	21,279	63
*Genesee	Near Mt. Morris, N. Y.	18	1924	1,400	17,025	52
Androscoggin	At Errol Dam, N. H.	18	1922	1,095	6,354	24
Genesee	St. Helena, N. Y.	16	1924	992	19,851	79
*Dead	The Forks, Me.	19	1923	878	12,317	55
*Frankstown Br., Juniata	Huntington, Pa.	18	1914	840	17,413	79
Hudson	North Creek, N. Y.	16	1923	804	13,709	65
Raquette	Piercefield, N. Y.	16	1924	723	5,620	29
Schroon	Riverbank, N. Y.	17	1923	534	5,491	36
Machias	Whitneyville, Me.	18	1921	465	5,841	43
Ausable	Ausable Fork, N. Y.	14	1924	444	9,251	71
Westfield	Knightville, Mass.	14	1923	162	3,582	61
Clyde	West Derby, Vt.	13	1924	150	1,507	27
Quaboag	W. Brimfield, Mass.	15	1923	150	1,121	20
*Rockaway	Near Boonton, N. J.	18	1923	121	1,597	35
	Average of group	17		1,542	21,615	55

GROUP 2

Santee	Ferguson, S. C.	17	1924	14,800	125,000	58
*Flint	Albany, Ga.	19	1921	5,000	33,804	37
Holston	Near Rogersville, Tenn.	18	1924	3,060	40,150	65
Etowah	Near Rome, Ga.	17	1921	1,800	34,041	84
Oostanaula	Resaca, Ga.	19	1923	1,610	22,616	61
Rappahannock	Near Fredericksburg, Va.	17	1923	1,590	21,022	58
Tygort	Fetterman, W. Va.	18	1924	1,340	30,289	95
*Oconee	Near Greensboro, Ga.	19	1923	1,100	18,298	68
Tygort	Belington, W. Va.	18	1924	390	11,472	97
	Average of group	18		3,410	37,410	69

* One or more years missing.

PART II.—SHORTER RECORDS—*continued*

GROUP 3

Stream	Place	Number of years in record	Last year in record	Catchment area in sq. mi.	Mean flood in cfs.	Coefficient of flood
*Platte	Near Columbus, Neb.	19	1915	56,867	22,384	4
*N. Platte	N. Platte, Neb.	19	1915	28,500	15,662	4
Minnesota	Near Mankato, Minn.	18	1920	14,600	20,612	9
Des Moines	Keosauqua, Iowa	13	1924	13,900	39,969	19
Minnesota	Near Montevideo, Minn.	16	1924	6,300	4,667	4
Tittabawassee	Freeland, Mich.	13	1924	2,530	16,434	31
*Wolf	Keshena, Wis.	16	1924	840	2,829	13
Apple	Near Somerset, Wis.	19	1924	550	1,111	7
	Average of group.	17		15,511	15,458	11

GROUP 4

*Colorado	Columbus, Tex.	16	1923	40,800	37,466	8
*Brazos	Waco, Tex.	19	1923	28,500	59,544	16
	Average of group.	18		34,650	48,505	12

* One or more years missing.

PART II.—SHORTER RECORDS—*continued*

GROUP 5

Stream	Place	Number of years in record	Last year in record	Catchment area in sq. mi.	Mean flood in cfs.	Coefficient of flood
*Arkansas	Holly, Colo	14	1924	25,000	11,532	3
N. Platte	Pathfinder, Wyo	19	1923	10,700	9,898	6
*Rio Grande	Embudo, N. M	18	1916	10,100	6,528	4
*N. Platte	Saratoga, Wyo	15	1923	2,880	10,180	17
*Duchesne	Myton, Utah	19	1923	2,750	5,850	10
Colorado	Near Kremmling, Colo	14	1918	2,380	11,751	23
*Santa Cruz	Tucson, Ariz	17	1923	2,260	2,703	6
Weber	Near Plain City, Utah	19	1923	2,060	5,316	12
*Roaring Fork	Glenwood Springs, Colo	17	1923	1,460	10,043	30
*Arkansas	Salida, Colo	17	1924	1,210	3,098	11
Weber	Devils Slide, Utah	19	1923	1,090	3,189	12
*Spanish Fork	Lake Shore, Utah	19	1923	700	691	4
Spanish Fork	Thistle, Utah	16	1923	490	652	5
*Lake Fork	Near Myton, Utah	16	1923	468	2,458	18
Cottonwood Cr	Near Orangeville, Utah	15	1923	200	1,249	18
*Huntington	Near Huntington, Utah	14	1923	188	793	12
Williams	Near Parshall, Colo	19	1923	185	1,123	17
Weber	Near Oakley, Utah	19	1923	163	2,326	40
Santa Clara	Near Central, Utah	15	1923	84	341	10
*Pine Cr	Near Round Valley, Calif	19	1923	32	208	13
S. Ruxton Cr	Halfway, Colo	19	1924	3.95	9.26	3
Cabin Cr	Near Halfway, Colo	18	1924	2.4	5.73	3
Lean Cr	Near Halfway, Colo	17	1924	2.0	3.56	2
Boehmer Cr	Near Pikes Peak, Colo	15	1924	7.2	29.9	6
L. Beaver Cr	Near Pikes Peak, Colo	15	1924	1.0	4.42	4
Sheep Cr	Near Halfway, Colo	17	1924	0.73	2.85	4
Sackett Cr	Near Pikes Peak, Colo	15	1924	0.65	3.93	6
	Average of group	17		2,386	3,333	11

* One or more years missing.

PART II.—SHORTER RECORDS—*continued*

GROUP 6

Stream	Place	Number of years in record	Last year in record	Catchment area in sq. mi.	Mean flood in cfs.	Coefficient of flood
Clark Fork	Newport, Wash.	18	1921	24,200	88,467	27
*Big Horn	Hardin, Mont.	18	1923	20,700	28,343	10
Clark Fork	Near Plains, Mont.	13	1924	19,900	87,892	30
Deschutes	Moody, Ore.	17	1923	9,180	18,638	13
John Day	McDonald, Ore.	19	1923	7,800	13,056	10
Flathead	Near Polson, Mont.	17	1924	7,010	52,217	44
Beaverhead	Barratts, Mont.	16	1923	2,850	1,896	3
*Marias	Near Shelby, Mont.	18	1923	2,610	8,208	15
Musselshell	Harlowtown, Mont.	16	1923	1,130	1,561	6
*W. Gellatin	Near Salesville, Mont.	19	1913	860	5,337	24
N. Fork Sun	Near Augusta, Mont.	19	1923	596	7,931	48
Two Medicine	Family, Mont.	17	1923	368	4,091	36
*Badger Creek	Near Family, Mont.	14	1923	241	1,237	15
*Tieton	Nashus, Wash.	16	1924	240	2,418	30
Tieton	Strabane, Mont.	16	1923	170	947	16
*Sweetgrass Cr.	Below Melville, Mont.	15	1923	137	887	17
Birch Cr.	Near Dupuyer, Mont.	16	1923	110	1,095	25
Ten Mile Cr.	Near Helena, Mont.	15	1923	103	363	9
*Sweetgrass Cr.	Above Melville, Mont.	15	1923	59.6	962	37
	Average of group.	17		5,172	17,134	22

GROUP 7

Umpqua	Near Elkton, Ore	18	1923	3,680	67,744	95
Rogue	Central Point, Ore	17	1923	2,020	22,588	51
Claekamas	Near Cazadeno, Ore	15	1923	685	23,521	127
Wenatchee	Near Leavenworth, Wash.	14	1924	591	12,589	76
Yakima	Cle Elum, Wash	18	1924	500	10,211	74
Entiat	Entiat, Wash	14	1924	419	3,161	25
N.Fork Snogualmie	Near North Bend, Wash.	17	1924	184	8,801	135
Baker	Near Concrete, Wash	14	1924	184	14,774	227
Bull Run	Near Bull Run, Ore	16	1924	102	9,159	223
S. Fork Snogualmie	Near North Bend, Wash.	17	1924	84	3,612	100
Bumping	Near Nile, Wash	15	1924	68	1,551	53
Kachess	Near Easton, Wash	19	1924	64	1,429	51
	Average of group	16		715	14,928	103

* One or more years missing.

GROUP 8

Stream	Place	Number of years in record	Last year in record	Catchment area in sq. mi.	Mean flood in cfs.	Coefficient of flood
American	Fair Oaks, Calif	18	1923	1,910	39,607	93
*San Joaquin	Near Friant, Calif	15	1923	1,640	15,463	41
Cache Cr	Yolo, Calif	15	1917	1,320	13,100	42
Potah Cr	Winters, Calif	17	1922	654	24,136	135
Mokelumne	Near Clements, Calif	19	1923	631	7,838	45
Cosomners	Michigan, Calif	16	1923	525	8,901	60
Calaveras	Jenny Lind, Calif	17	1923	395	19,770	163
Bear	Van Trent, Calif	19	1923	263	13,605	158
Little Stony Cr	Near Ladoga, Calif	16	1923	102	2,528	61
Eleanor Cr	Near Hetch Hetchy, Calif.	14	1923	79	1,660	50
Butte Cr	Butte Valley, Calif	15	1920	73	667	22
Sweet Water	Near Descanes, Calif	18	1923	43.7	406	19
	Average of group	17		636	12,307	74

* One or more years missing.

PART III.—AVERAGE OF COEFFICIENTS BY GEOGRAPHICAL GROUPS

Group and approximate location	Average values Full term records			1% chance factor	C. F. short term records
	C. F.	C. V.	C. S.		
1. Maine to Maryland	68	0.36	1.44	2.29	55
2. Virginia to Georgia	75	0.42	0.92	2.35	69
3. Michigan, Dakota and Iowa	13	0.53	0.90	2.66	11
4. Texas and New Mexico	5	0.72	1.48	3.57	12
5. Colorado, Utah, Arizona	12	0.50	1.22	2.78	11
6. Idaho	27	0.36	0.80	2.13	22
7. Washington, Oregon, Coastal	103	0.51	1.73	2.98	103
8. California (in part)	57	0.76	1.76	3.94	74

These values, together with the limits of the eight groups, are shown on a map of the United States in Fig. 37, page 86.

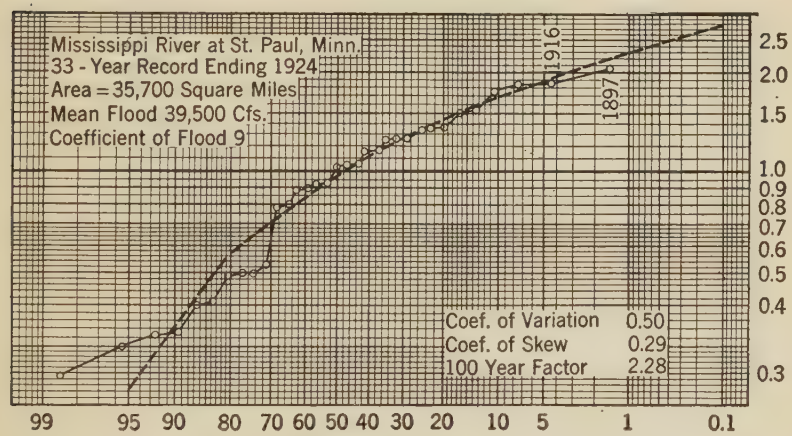

FIG. 8.—This Figure and the Twenty-eight that Follow Show Plottings of Annual Floods of the Longest and Best Records Now Available.

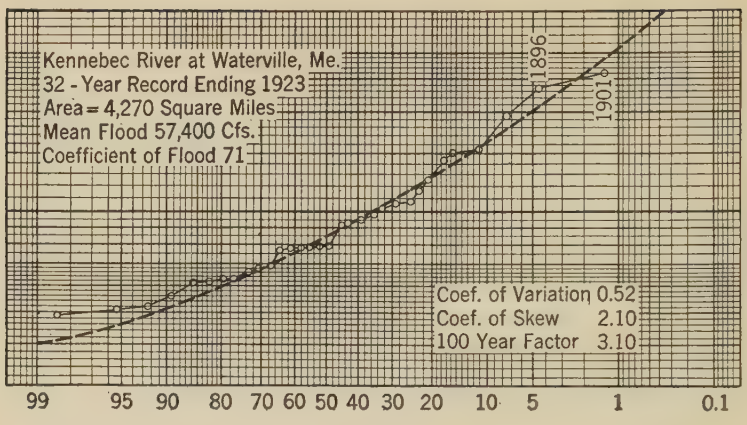

FIG. 9.

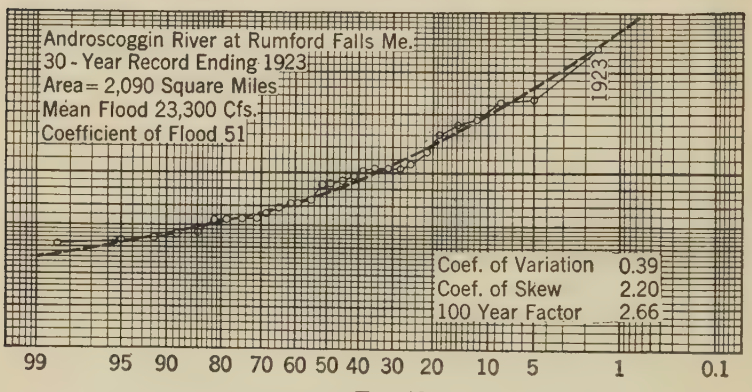

FIG. 10.

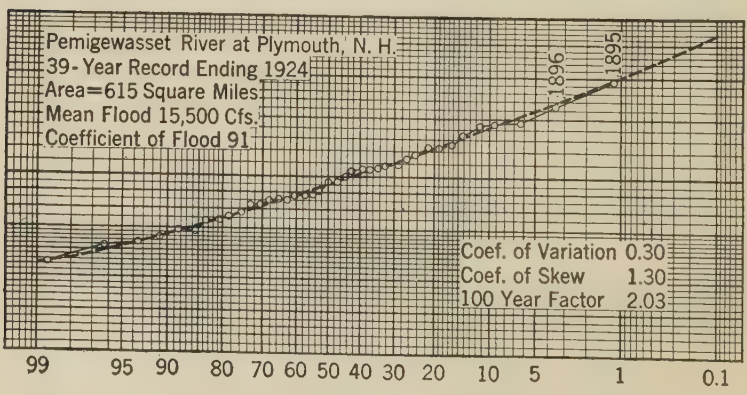

FIG. 11.

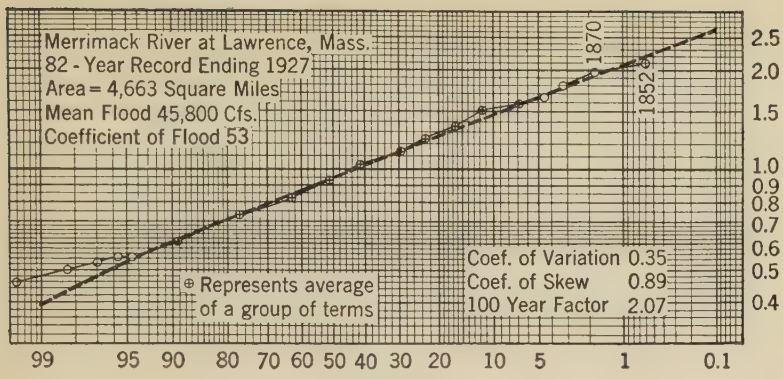

FIG. 12.

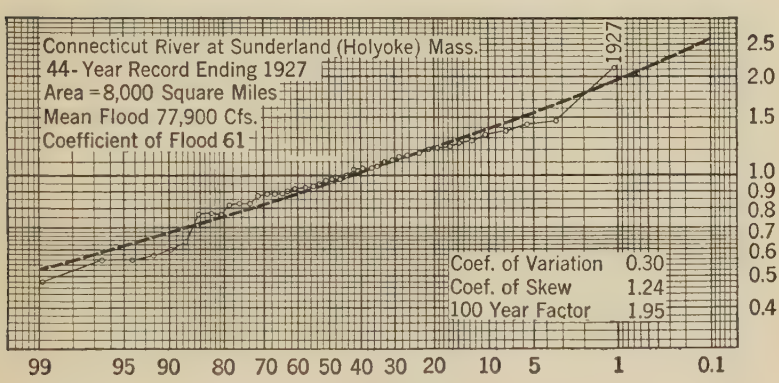

FIG. 13.

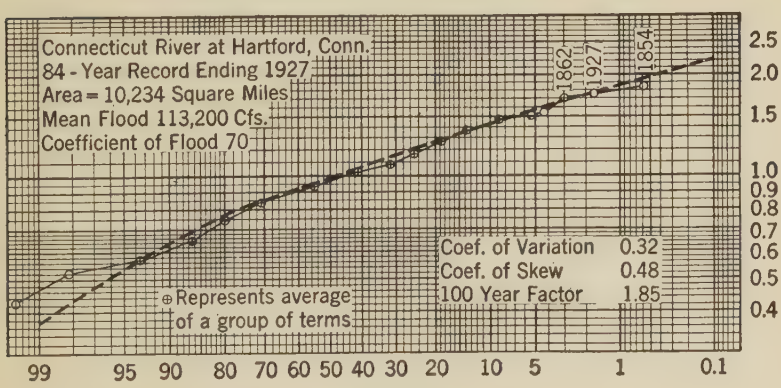

FIG. 14

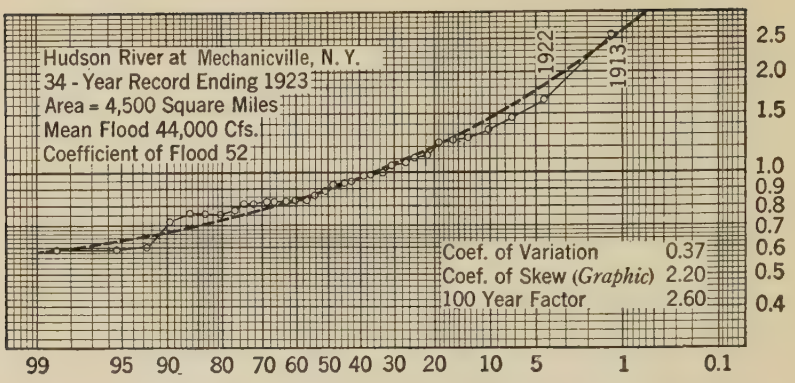

FIG. 15.—(Another Interpretation of These Data is Shown in Fig. 40).

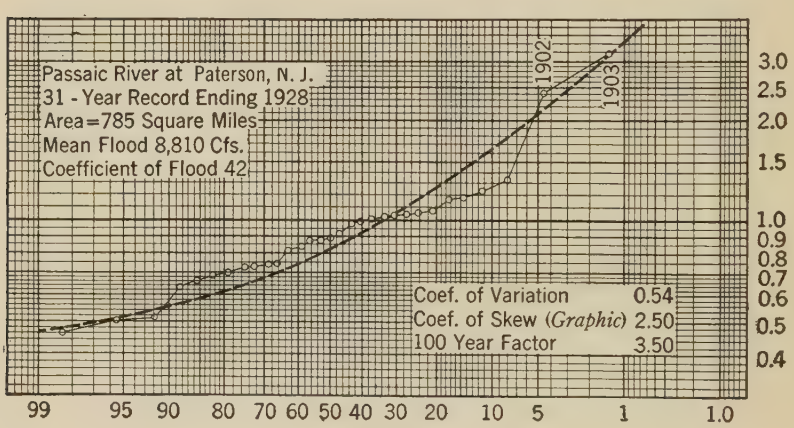

FIG. 16.

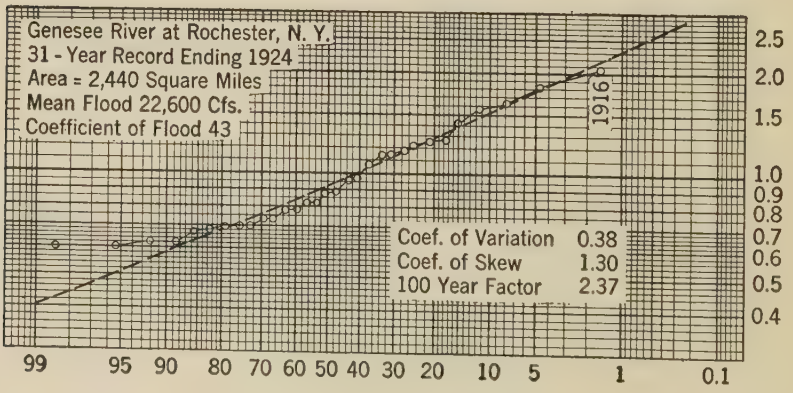

FIG. 17.

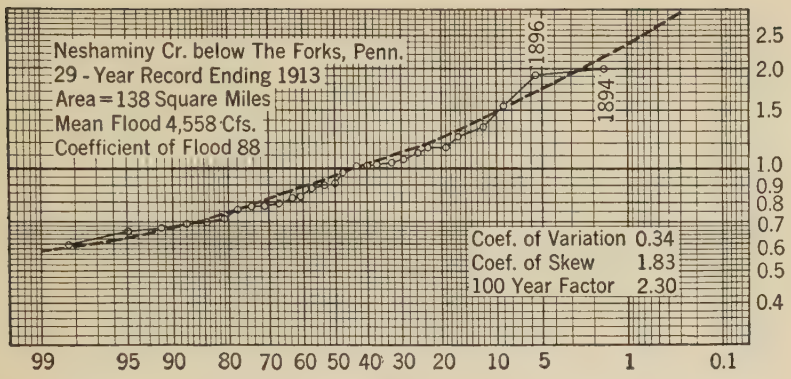

FIG. 18.

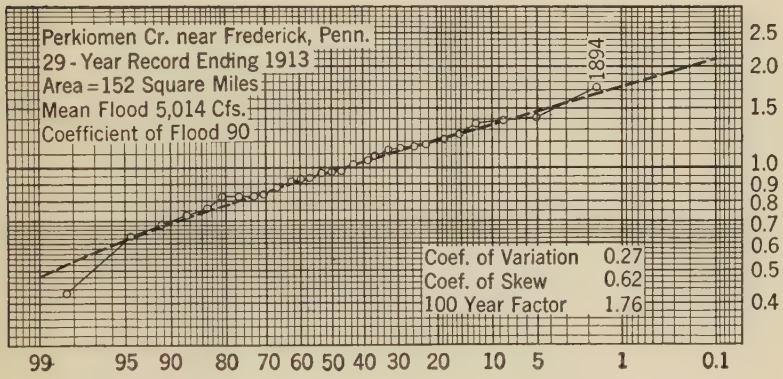

FIG. 19.

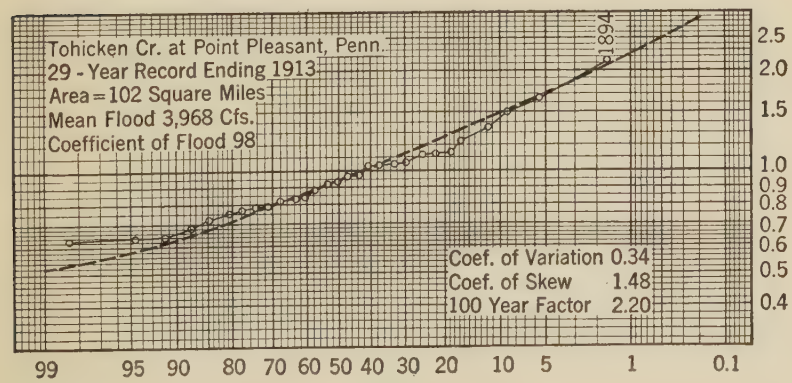

FIG. 20.

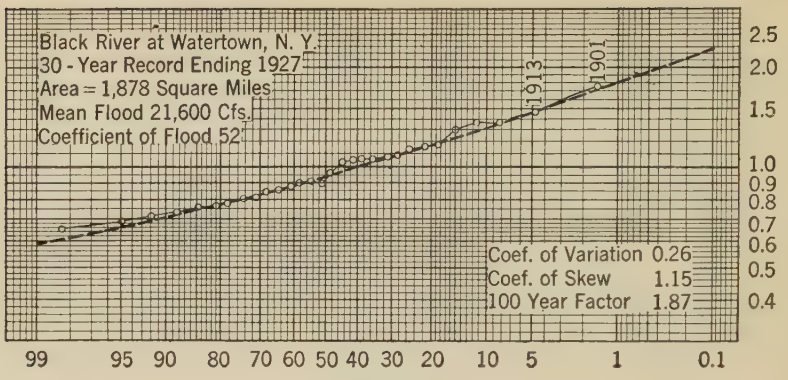

FIG. 21.

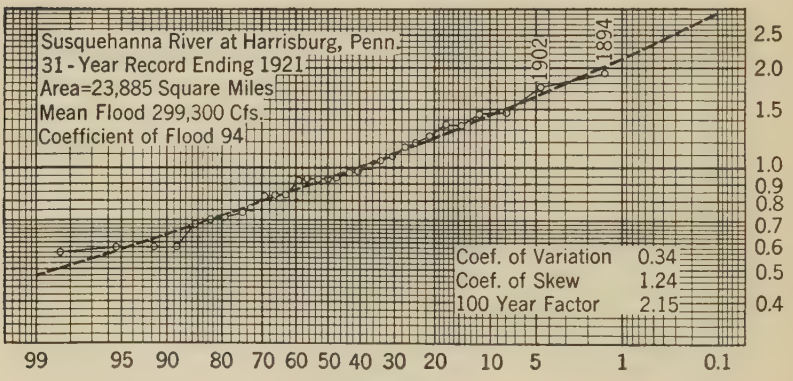

FIG. 22.

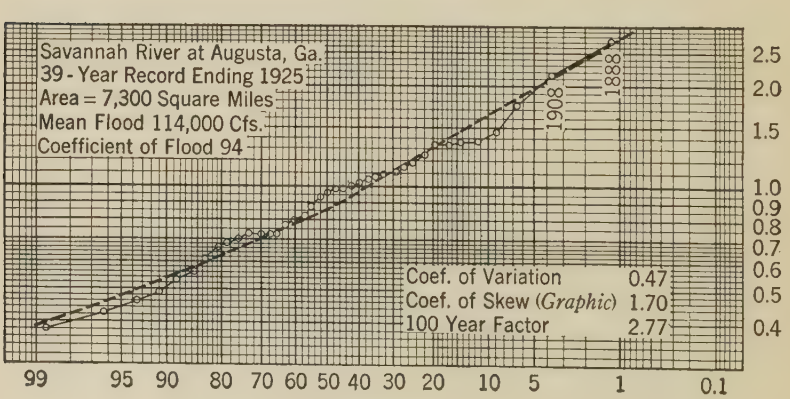

FIG. 23.

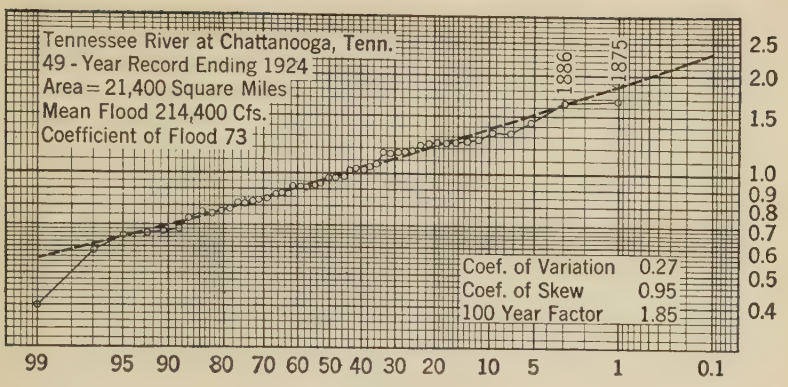

FIG. 24.

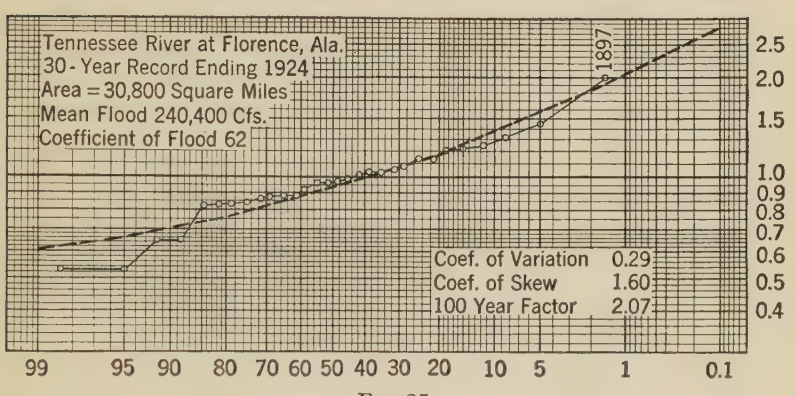

FIG. 25.

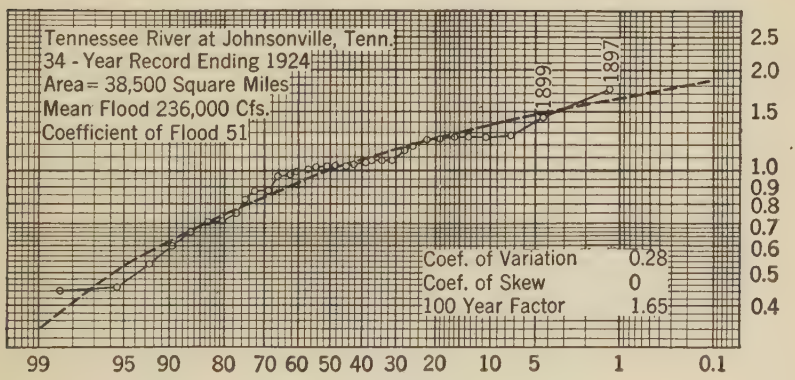

FIG. 26.

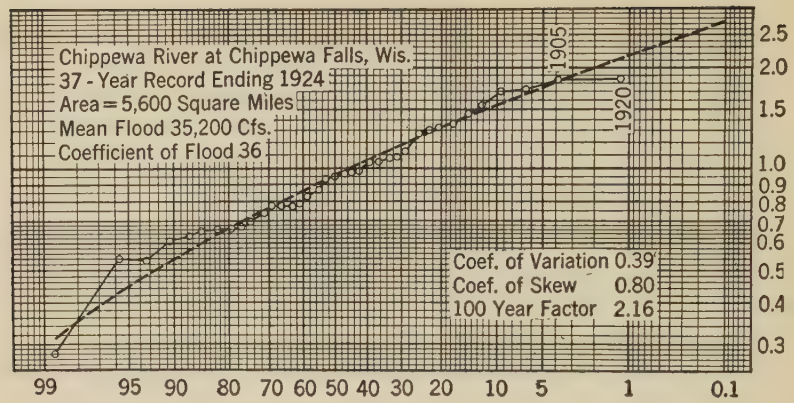

FIG. 27.

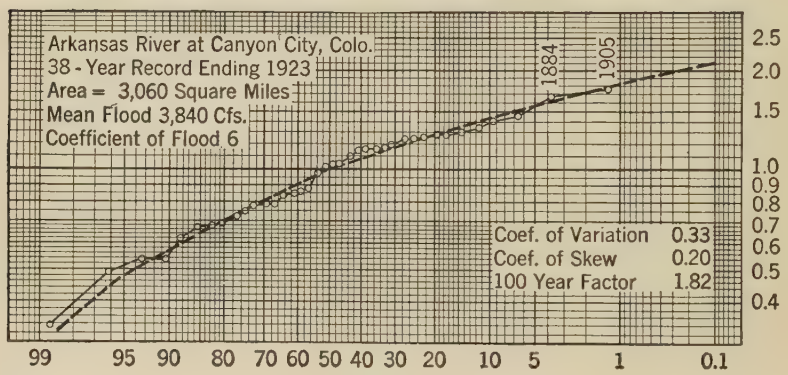

FIG. 28.

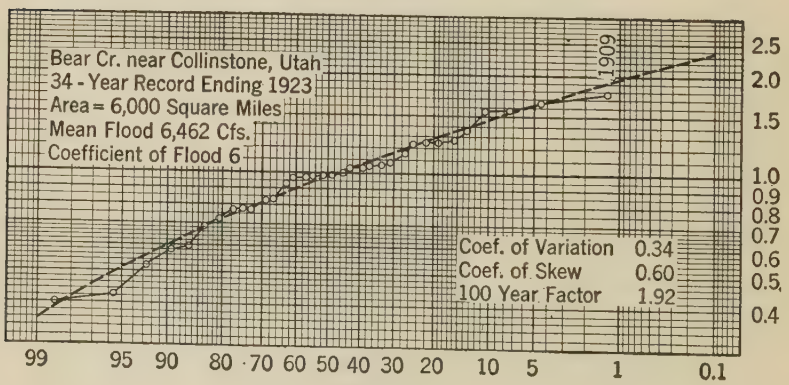

FIG. 29.

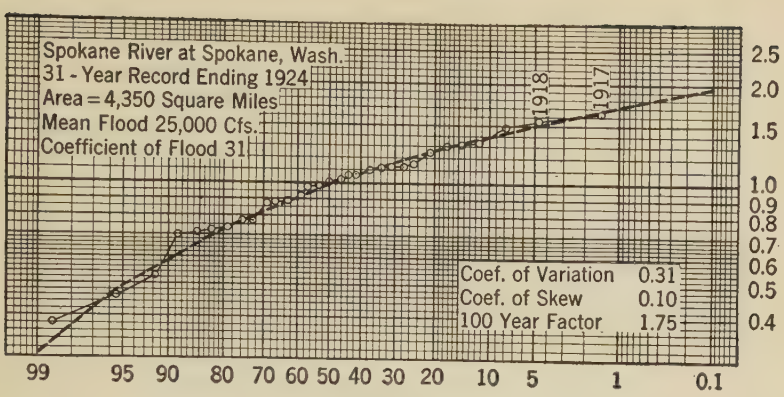

FIG. 30.

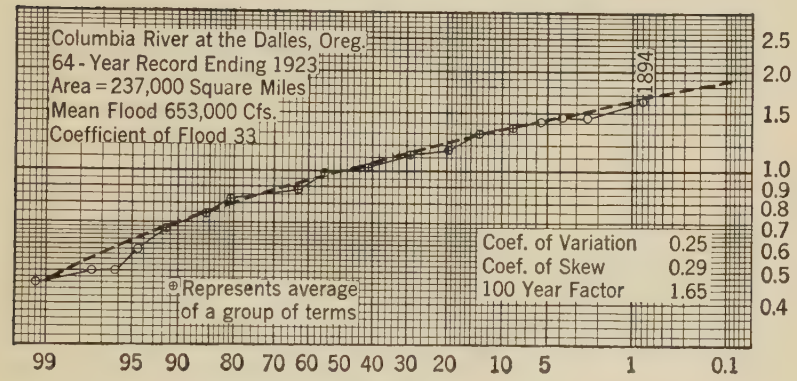

FIG. 31.

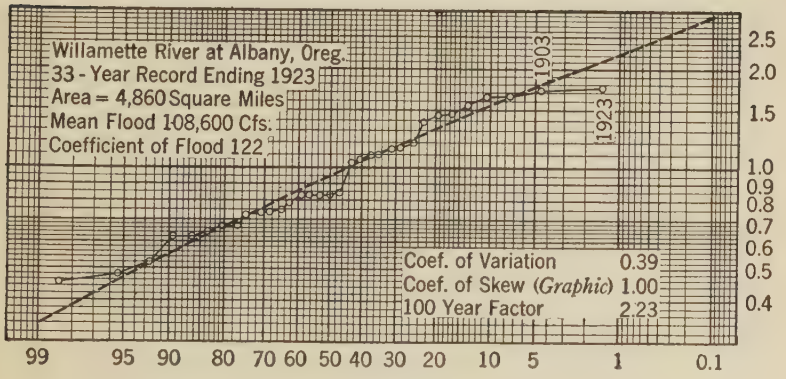

FIG. 32.

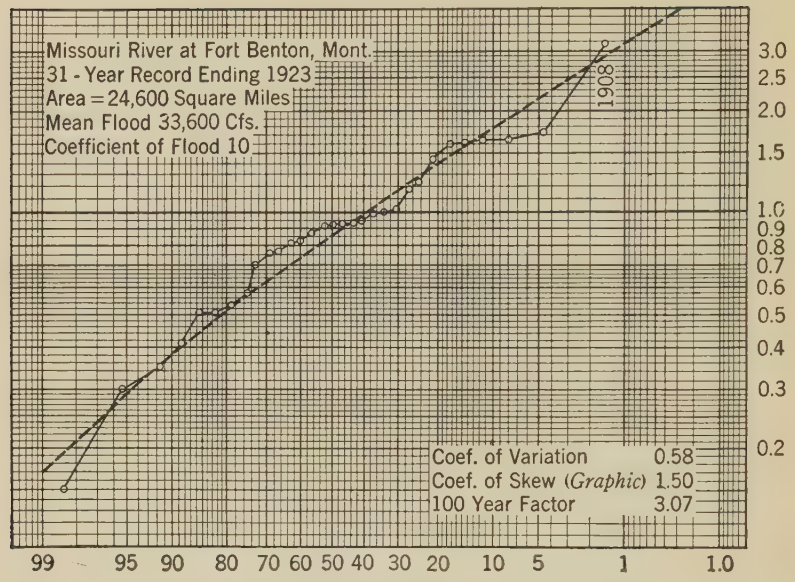

FIG. 33.

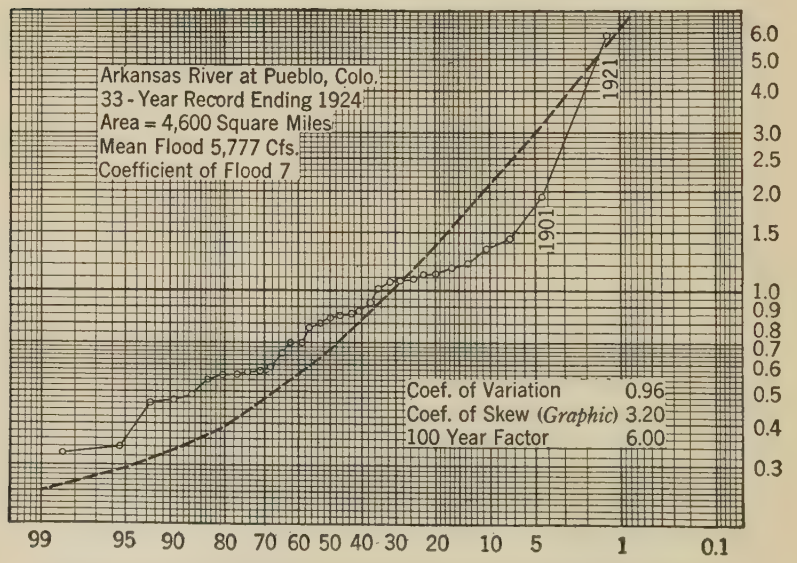

FIG. 34.—(Another Interpretation of These Data is Shown in Fig. 41.)

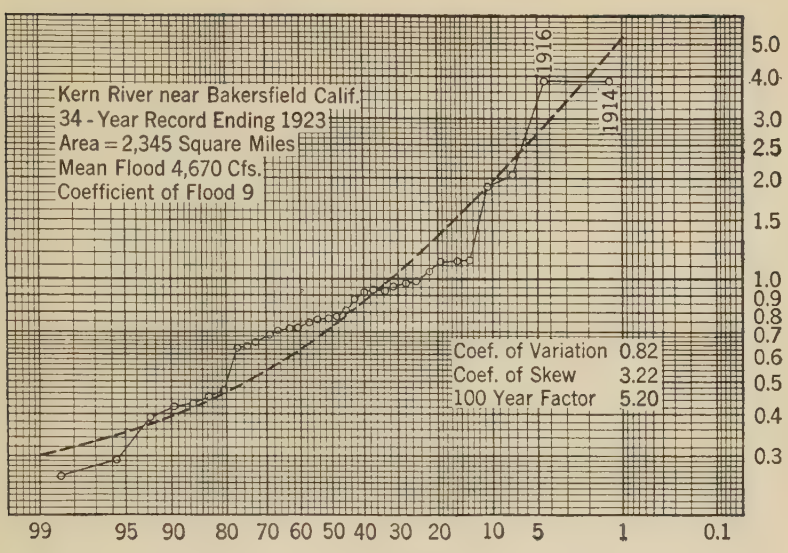
Kern River near Bakersfield Calif.
34 - Year Record Ending 1923
Area = 2,345 Square Miles
Mean Flood 4,670 Cfs.
Coefficient of Flood 9
1916
1914
Coef. of Variation 0.82
Coef. of Skew 3.22
100 Year Factor 5.20
5.0
4.0
3.0
2.5
2.0
1.5
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
99 95 90 80 70 60 50 40 30 20 10 5 1 0.1

FIG. 35.

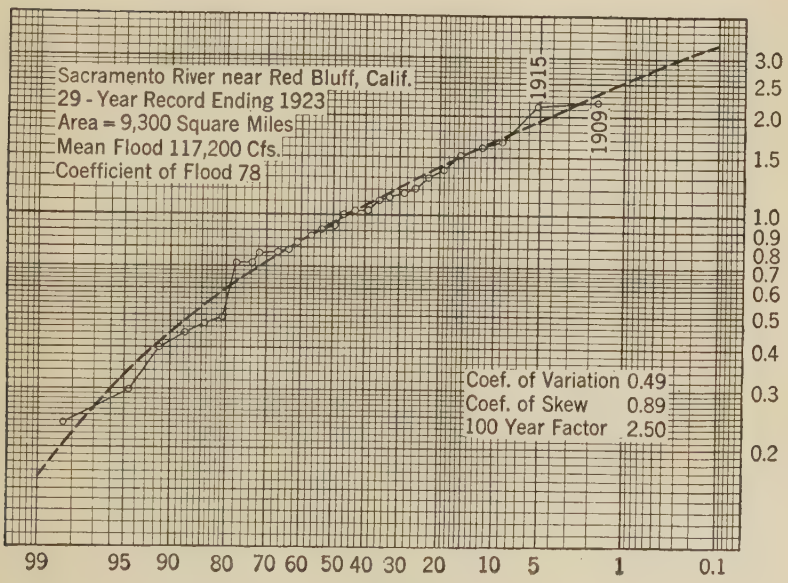
Sacramento River near Red Bluff, Calif.
29 - Year Record Ending 1923
Area = 9,300 Square Miles
Mean Flood 117,200 Cfs.
Coefficient of Flood 78
1915
1909
Coef. of Variation 0.49
Coef. of Skew 0.89
100 Year Factor 2.50
3.0
2.5
2.0
1.5
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
99 95 90 80 70 60 50 40 30 20 10 5 1 0.1

FIG. 36.

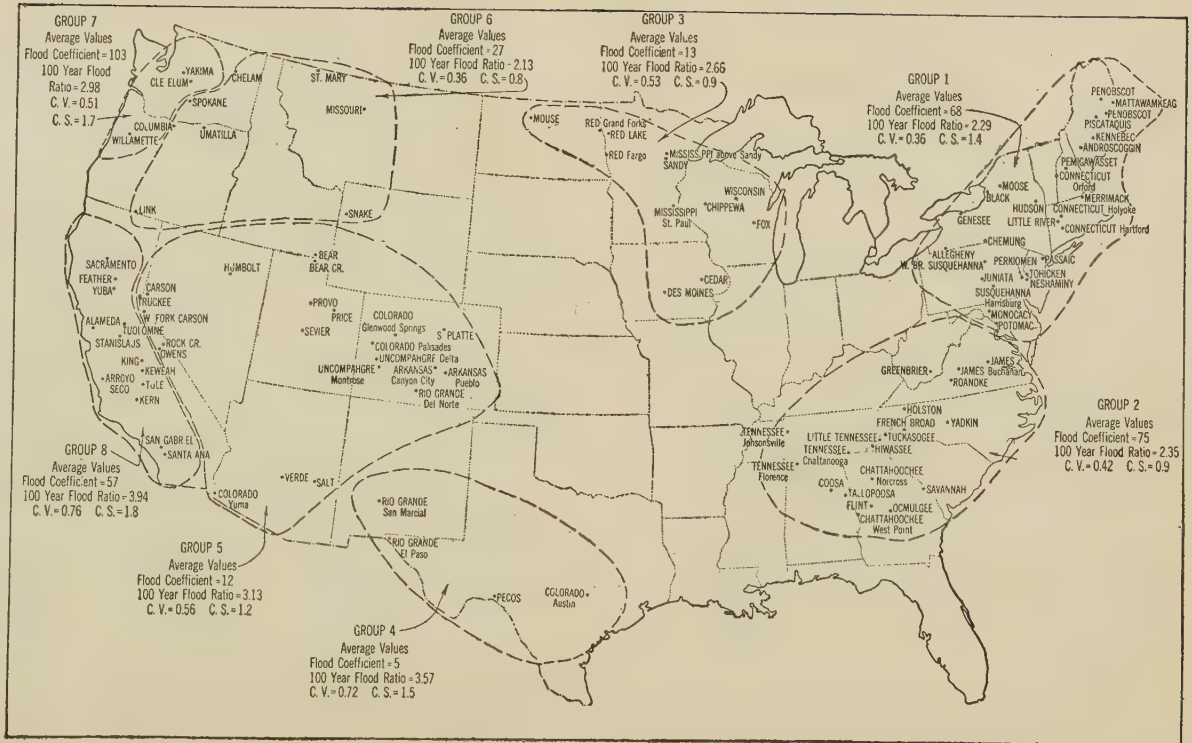

FIG. 37.—Showing Geographical Grouping of Records with Average Values of the Coefficients.

CHAPTER X

EFFECT OF ONE LARGE FLOOD

Sometimes a river makes a flood record for a term of years that seems to be complete in itself, and that has all the appearance of giving a correct indication of future floods. Then there will be one large flood that goes so far beyond the earlier ones that it upsets the whole basis of estimate and gives a new idea of the flood-producing power of that catchment area.

Two Great Floods as Illustrations.—Of the 109 streams from which records have been examined, two are selected for further study, as the most striking examples of this condition. These are the Hudson River at Mechanicville, N. Y., and the Arkansas River, at Pueblo, Colo.

In the case of the Hudson River, the measurement at the Mechanicville Dam gave a perfectly definite basis. There can be no question about the approximate accuracy of the records.

In the case of the Arkansas River, at Pueblo, there was a gaging station of the U. S. Geological Survey with automatic gage, and all necessary equipment, that had seen years of successful service, but the flood was greater than had been provided for, and went entirely out of anticipated limits, so that the flood quantity had to be estimated without aid from the regular equipment. Some of the estimates of quantity that were made afterward were based upon estimated flows, using assumed coefficients in the Kutter formula for various channels, including city streets, through which water flowed.

The breaking of a dam and storage reservoir upon one of the tributaries contributed to this flood, but apparently not to any very important extent. The conditions of the flood were described in the Engineering News-Record,[1] to which reference is made for additional details.

The volume of flood flow, as published by the U. S. Geological Survey several years afterward and used in the present study, was less than some of the estimates made a few weeks

[1] Engineering News Record, Vol. 87 (1921), p. 23.

after the flood. The published record does not state how this estimated quantity was reached, but there is no reason to doubt that the later and more deliberate estimate is best.

This Arkansas River flood was a very large one, and probably deserves its place at the head of the list of all the floods in the rivers covered by the records of 109 streams; but, on the other hand, the reported quantity of flow must be considered as an estimate that may not be very close.

The Hudson River flood also was a very large one, but in this case there is more question as to whether it should be given second place. There are some shorter records with one very great flood. This matter, however, does not need to be determined for our present purpose. It will be profitable to examine these two records as they appeared shortly before the great floods occurred and to compare them with records after these floods.

For the Hudson River three calculations are made, one for the year before the flood, one for the year including the flood, and a third for a time ten years later. For the Arkansas only two calculations are made, as there are only three years in the record subsequent to the flood.

The calculations have been made and a statement of the data in tabular form is as follows:

Table Showing Effect of One Great Flood

	Hudson River, 4,500 sq. mi.			Arkansas River, 4,600 sq. mil	
	Just before flood	Just after flood	Entire record	Just before flood	After flood
Number of years in record	23	24	34	29	33
Last date of record	1912	1913	1923	1920	1924
Mean flood, cfs	41,699	44,711	44,000	4,877	5,777
Coefficient of flood	50	53	52	5.7	6.8
Coefficient of variation	0.23	0.39	0.37	0.42	0.96
Coefficient of skew	0.10	3.5	3.0	1.16	5.5
Coefficient of skew, graphic		2.5	2.2		3.2
Ratio of one per cent chance flood to mean flood, estimated	1.55	2.79	2.60	2.39	6.00
Estimated one per cent chance flood in cfs.	64,600	124,500	114,000	11,650	34,600
Ratios before and after C. F	1.00	1.06	1.04	1.00	1.18
Ratios before and after C. V	1.00	1.70	1.61	1.00	2.29
Ratios before and after C. S	1.00	25.00	22.00	1.00	2.75
One per cent chance flood ratio	1.00	1.80	1.67	1.00	1.68
One per cent chance flood cfs	1.00	1.93	1.76	1.00	2.97

Figures 38 and 39 show the flood records of the two rivers up to and including the years immediately before the great floods and may be compared with the similar diagrams, Figs. 15 and 34, previously given for the entire record periods.

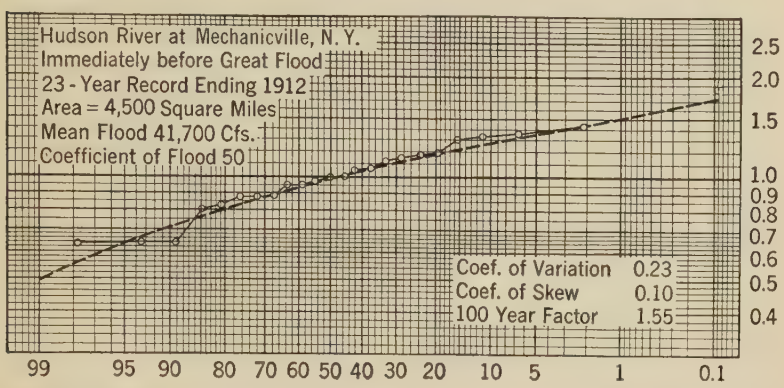

FIG. 38.—For Comparison with Fig. 15 to Show the Effect of One Large Flood.

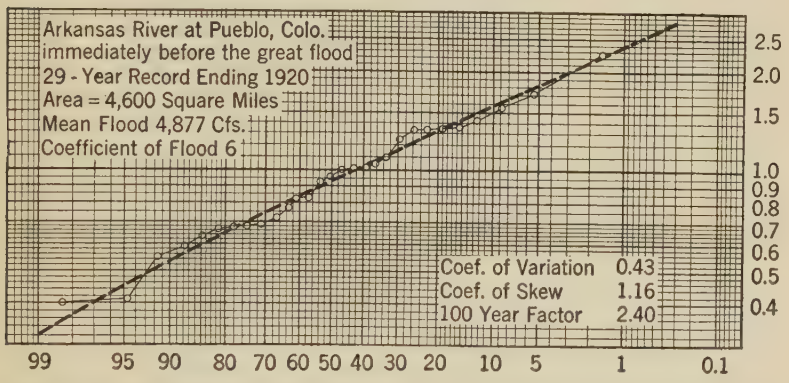

FIG. 39.—For Comparison with Fig. 34 to Show the Effect of One Large Flood.

It will be seen that, taking the record of the Hudson River just before the flood as the sole guide for an estimate, and the record just after the flood in the same way, and basing the estimates in each case on the one record and nothing else, the estimated one per cent chance flood is nearly twice as great after the event as it was before. In the case of the Arkansas River it is three times as great.

The above are extreme cases. By a procedure to be subse-

quently described it might have been inferred in advance that the records of both of these rivers before the floods were below normal whereas, on the other hand, after the floods they were above normal. Actual estimates based on all available data, including records of other streams that were comparable, would not have differed by so great an amount as this comparison indicates.

Another method of approaching this problem is to take into account the whole number of record years in all the records from all the streams before us. The records represent 109 streams with average lengths of 26.6 years and a total record period of 2895 years. Of all these streams, the two cases cited apparently indicate the greatest relative floods within the record periods of all of the streams. It is not unreasonable to assume that these two floods correspond to something like the first and second floods in a record period for one stream with a total length of 2895 years. This line of thought follows the method that W. E. Fuller used in his paper on flood flows.

The Arkansas flood is the greater of the two and by the rule its plotting position is $P = \frac{2m - 1}{2n}$; $m = 1$; $n = 2895$, and $P = 0.0173$ per cent. The Hudson River flood is second and would have a plotting position for $m = 2$; $P = 0.052$ per cent.

Plotting these two highest floods, Figs. 40 and 41, at these plotting positions instead of where they actually occurred, and connecting these plotted extreme points with lines representing as well as possible the remainder of the data, brings these plottings more or less into line with those for other streams.

Using the plottings so obtained for the estimate after the floods, in comparison with those representing the data before the floods, we have the following results:

	Hudson River		Arkansas River	
	23-year record	34-year record	29-year record	33-year record
Ratio of one per cent chance flood to annual flood	1.55	1.90	2.39	2.80
Estimated one per cent flood, cfs	64,600	85,000	11,650	16,100
Ratio of estimates for one per cent chance flood before and after	1.00	1.31	1.00	1.38

Analysis and Comments.—No special merit can be claimed for these estimates. They are set up only as representing ideas that are not unreasonable. Accepting them for the moment,

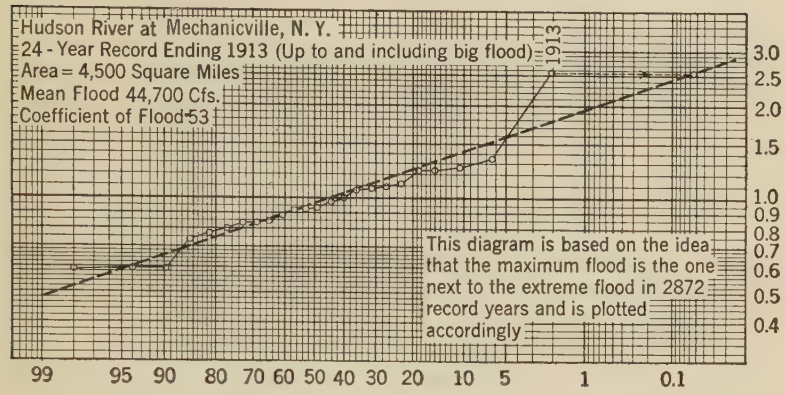

FIG. 40.—Revision of Fig. 15 on Additional Assumptions.

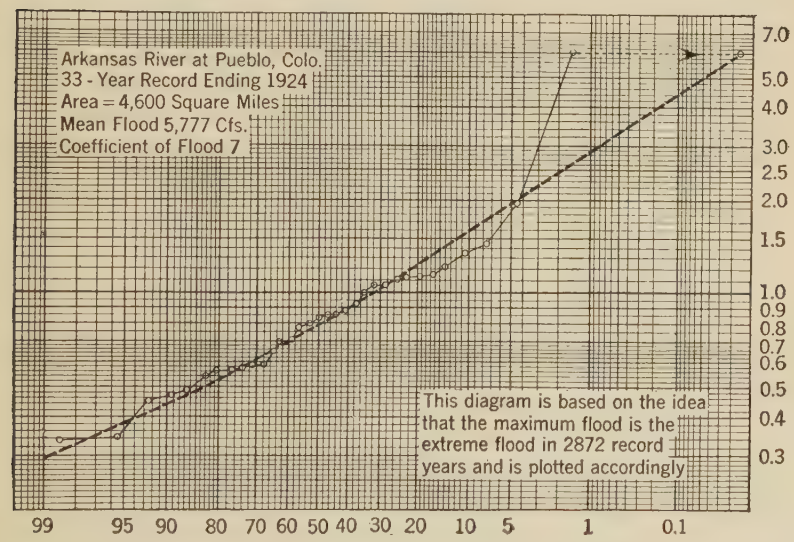

FIG. 41.—Revision of Fig. 34 on Additional Assumptions.

they indicate that for the two records at the top of the list, 31 and 38 per cent would have had to be added to estimates made before the flood by this method in order to have reached the very conservative estimates made after it was all over.

The question remains whether similar additions should be made to estimates based on other records that may be in the position these records were in before the great floods occurred. We may get help in this by studying the coefficient of skew. One idea that has grown out of this study and out of examination of the curves of all the streams that have been plotted, is that a high skew is an indication that that particular record has a greater flood or more than the normal number of high floods in its record period, whereas a record with very low skew is one that is deficient in such large flood flows. The records, then, that show low coefficients of skew are likely to produce estimates of rare floods below the truth, and the addition of a percentage to estimates based on such data is indicated.

It appears that such additions are proper and necessary in the case of records having coefficients of skew that are unusually low and that are much below normal for the region. Similar but smaller additions might appropriately be made when the skews are somewhat below normal, the addition being reduced as the coefficient of skew increases and approaches the normal. Carrying the matter further, the estimates of flood quantities might properly be reduced below the calculated amounts in those cases where the skew is found to be greatly in excess of what may be taken as normal for its group or region.

It is clear that in these two great floods we are dealing with a condition similar to, but not as extreme as, that to be discussed in Chapter XIII. In the present cases, it is possible to assign probability positions to these floods from the data at hand, and to get a rather rough idea of what a long-term series would probably look like.

The data mentioned in Chapter XIII cannot be handled in this way. They may be looked upon as extreme cases of rare floods beyond any points that can be located and plotted at the present time.

The whole business is not definite enough for any precise statement, but in those cases where great damages would result from an underestimate no chances should be taken and estimates made by these methods should be liberally increased.

The above study gives a notion of the limitations of the method. It is more than clear that one thirty-year record is by no means enough for the foundation of a long-term estimate.

It may be that using the coefficient of skew that seems to be normal to the region for all estimates in that region will lead to better estimates of flood flows than the use of the coefficients computed from individual records. In following this through, one might use the average values of skew for the group in which the stream under consideration was found. Or a certain number of streams might be selected, as more nearly comparable to or as having more accurate records than the others, to establish the probable normal coefficient of skew for use in a given case.

In speaking of a high or low coefficient of skew in this connection, the normal coefficient of skew of the streams in the general neighborhood may be taken as a starting point rather than the average for the whole country.

The same procedure may also be followed in establishing a normal coefficient of variation in cases where the local record seems to be abnormal or for any reason unreliable.

CHAPTER XI

THE THREE COEFFICIENTS AND THE FLOOD RATIO FACTORS

In studying the three coefficients which are calculated from the records of each stream, and which serve to give an indication of the estimates to be made for the floods of the stream, it is apparent that there are great variations in records of several streams even in one small part of the country. These differences may be accounted for in general in two ways:

(1) Permanent conditions depending upon peculiarities in the various catchment areas and in their rainfalls, climates, and storages, both natural and artificial.

(2) Temporary conditions due to the shortness of the record periods and to the effect of chance. These will tend to decrease and disappear as the records become longer.

Differences in the Coefficients Analyzed.—It is impossible to tell with any degree of exactness which of the differences are due to the first of these conditions and which to the latter.

The differences in the *coefficients of flow* probably depend mainly upon actual differences in the catchment areas represented. These coefficients may be taken as the best indices of the flood-producing capacities of different areas. Among the conditions tending to affect this coefficient may be mentioned the fact that mountainous areas and areas with impervious soil tend to increase it. That is to say, the streams coming from such areas are flashy and subject to higher floods than result from the opposite conditions. High average rainfall tends to increase it. Storage tends to reduce it. Storage may be natural in sand and gravel deposits, in lakes and ponds, or on meadows; or it may be artificial in reservoirs. If one looks over the values in the table in Chapter IX, he will find that the lowest values

in some of the groups are associated with streams that come from relatively large lakes that smooth out the flood flows and greatly reduce them. The table does not show the storage on each stream, natural and artificial, and data to make such a desirable addition to the table are not at hand. One has to be familiar with the streams and their catchment areas in order to form a general idea of these relations. In some cases the flood flows from such streams will be no more than half of what might be expected from similar areas with no storage control.

The differences in the *coefficient of variation* are perhaps more evenly divided between permanent differences dependent upon the catchment and climate and temporary conditions peculiar to short-term records. One heavy storm passing over an area may increase the coefficient of variation of the flood records by a considerable amount, and on different streams by different percentages according to the relative severity of the storm on the various catchments.

The coefficient of variation will be affected by such temporary conditions to a greater extent than will the coefficient of flood, but even allowing for these variations, the values calculated from records of a fair length of twenty years or more are usually well-fixed and dependable within certain limits.

In the *coefficient of skew* a different condition is found. This is much more affected by such temporary conditions as a single great storm and flood. Individual records seem to depend more upon the occurrences of such floods in the record periods than they do upon the climate and the peculiarities of the catchment area. Wide differences are found in the coefficients of skew in streams side by side and apparently similar. They can be accounted for only in this way.

Two of the highest coefficients of skew, which have been mentioned at length in Chapter X, are found in two streams that have had extraordinarily large floods in their record periods. These high coefficients of skew are associated with the highest relative floods that have occurred in all the data before us.

Passing to other records that show high coefficients of skew, but not as high as in these two cases, it seems probable that they also represent one flood in each case larger and sometimes much larger than would normally occur in the record period. In other words, a coefficient of skew considerably in excess of

the average for its group or region, say 50 per cent or more, may be taken as presumptive evidence that the bit of record representing the stream from which it is derived contains a considerably larger flood than would be normally found in that number of years taken from a longer record of the same stream.

On the other hand, there are records that show coefficients of skew considerably less than normal for the group or district, say less than half of the general average. These are cases where the sample of the record at hand does not contain any flood as large as would normally be expected in a record of that length.

Dual Character of Coefficient of Skew.—This is a result that was not expected when the study was undertaken. It forced itself upon our attention as the work proceeded. It now looks as if the coefficient of skew is an index as to whether or not the record in question contains more or less than its fair proportion of floods.

The problem may be compared to the use of the barometer. The barometer is used for showing atmospheric changes. It is also used for indicating altitude. The two uses do not go together very well. If one is traveling and observing altitudes, the indication of weather by a change in the barometer may be covered up by change in altitude and not be determinable. The change that might have indicated weather appears only as an error in the observations of altitude.

It may be much the same with the coefficient of skew. Its indications were expected to throw light upon permanent characteristics of flow which grew out of physical differences in the catchment areas and the climate in different parts of the country, but it appears, after trying it out, that these coefficients are so far affected and colored by the temporary short-term character of the samples that the latter characteristic becomes an important and perhaps dominant part of their makeup.

The dual character of these coefficients must be recognized, and although in the longer records and in averages they do give necessary indication of permanent characteristics, they also give an indication, rough in character but perhaps the best available, as to whether a given record carries more or less than its fair proportion of considerable floods.

How to Estimate.—In making an estimate of future flood quantities for a particular stream it is too early to generalize or to give rules. One should consider the record of the stream

itself, if there is a record available, and also the records of other streams as near and as fairly comparable as can be found.

In doing this it is to be expected that additional data may be found to bring the records up to date and to add new ones. Short records and incomplete records may be of material aid in sizing up a local condition. Values should be selected for the three coefficients, after considering all of the data, that will represent as nearly as possible, but with safety, the conditions to be expected.

In many cases the average values of the coefficients for neighboring streams will be the best basis of estimate. This is due to the scantiness of present data rather than to any assumption of equality in the coefficients. We know that there must be differences in the coefficients of neighboring streams that grow out of natural differences in the conditions. We can infer this from the ease with which coefficients may be changed by the works of man.

For instance, take the flow of an average stream in Group No. 1. This flow may be modified by the construction of an inadequate dry flood control dam sufficient to control the smaller floods, but not the larger ones. The small floods will be reduced in greatest measure while only a relatively small proportion of the larger floods will be removed. Obviously, this change will reduce the coefficient of flood and will increase the coefficients of variation and skew; and it will be found that estimates of rare and high floods will be only moderately changed. This is only one of many things that may be assumed to be done that will change the coefficients.

Most of the records now presented relate to streams of some considerable size. Very few of them are for areas of less than one hundred square miles. Estimates of floods for smaller areas must frequently be made. It is not well to generalize, but so far as we have gone with shorter-term records from smaller areas not shown among the data used in this work, the methods of calculation indicated are applicable to smaller areas, even to the smallest.

It must be remembered, however, with small areas that the maximum rate of flow and also the maximum two-hour flood, etc., will be higher relatively than for larger areas. The factors for these short-term floods must be selected accordingly. In this connection the study of maximum floods, outlined in

Chapter XIII, will be useful and sometimes the safest procedure to follow.

A tabular statement of the three coefficients for the eight geographic groups into which the data were divided is shown in the following table:

	Group[1]							
	I	II	III	IV	V	VI	VII	VIII
Coefficient of:								
Flood.....	68	75	13	5	12	27	103	57
Variation.....	0.36	0.42	0.53	0.72	0.50	0.36	0.51	0.76
Skew.....	1.4	0.9	0.9	1.5	1.2	0.8	1.7	1.8

[1] The streams included in each group are listed in Chapter IX. The areas represented by each group are shown in Fig. 37, page 86.

Average flood curves may be computed from the average coefficients of variation and skew that were obtained by averaging the separate records in the various groups. Such average or normal flow curves for the eight groups are shown in Figs. 42 and 43, pp. 100 and 101.

Using the Factors in the Tables.—It is possible to take from these plottings the ratios to be used for any group and for a flood of any degree of rarity. The plottings give very definite indications but it must be remembered in using them that they are not more accurate than the data on which they rest and the data for some of the groups are much less than would be adequate to establish fair normals for their regions.

The factors for a few representative points on these curves for each geographic group are shown in the following table:

FACTORS BY WHICH TO MULTIPLY ANNUAL AVERAGE FLOOD AS CALCULATED FROM AVERAGE COEFFICIENTS OF VARIATION AND SKEW

Annual chance of exceeding limit, per cent	Group							
	I	II	III	IV	V	VI	VII	VIII
10	1.49	1.54	1.70	1.97	1.67	1.46	1.69	2.02
1.00	2.26	2.29	2.62	3.58	2.67	2.07	2.93	3.95
0.10	3.13	2.97	3.48	5.43	3.71	2.61	4.45	6.38
0.01	4.11	3.67	4.38	7.60	4.83	3.16	6.30	9.40

It may be stated again for clearness that to obtain an estimate of the flood from any stream for which it is desired to apply these factors, the estimate is made by multiplying the 0.8 power of the area in square miles by the coefficient of flood that it is desired to use, and the product by a factor from the above table corresponding to the annual chance that it is desired to use.

Estimates of the flow per square mile based on the average coefficients of flood for each district for a one per cent chance flood are shown in the following table:

ONE PER CENT CHANCE ONE-DAY FLOOD COMPUTED FROM THE AVERAGE COEFFICIENTS FOR EACH GROUP

Cubic Feet per Second per Square Mile

Area in square miles	Group							
	I	II	III	IV	V	VI	VII	VIII
1	154	171	34	18	32	56	300	225
10	97	108	21.5	11.3	20	35	190	142
100	61	68	13.6	7.1	12.7	22	120	89
1,000	39	43	8.6	4.5	8.0	14	75	57
10,000	25	27	5.4	2.8	5.1	9	48	36
100,000	15	17	3.4	1.8	3.2	5.6	30	23

It is to be noted that maximum floods are greater than one-day floods. These figures all relate to one-day floods and not to maximum floods.

Similar estimates for the 0.1 per cent chance one-day flood are shown in the following table:

Area in square miles	Group							
	I	II	III	IV	V	VI	VII	VIII
1	213	222	45	27	44	70	460	365
10	134	140	28	17	28	44	290	230
100	85	88	18	11	18	28	182	145
1,000	54	56	11.3	7	11	18	115	90
10,000	34	35	7.1	4.3	7	11	72	58
100,000	21	22	4.5	2.7	4.4	7	46	36

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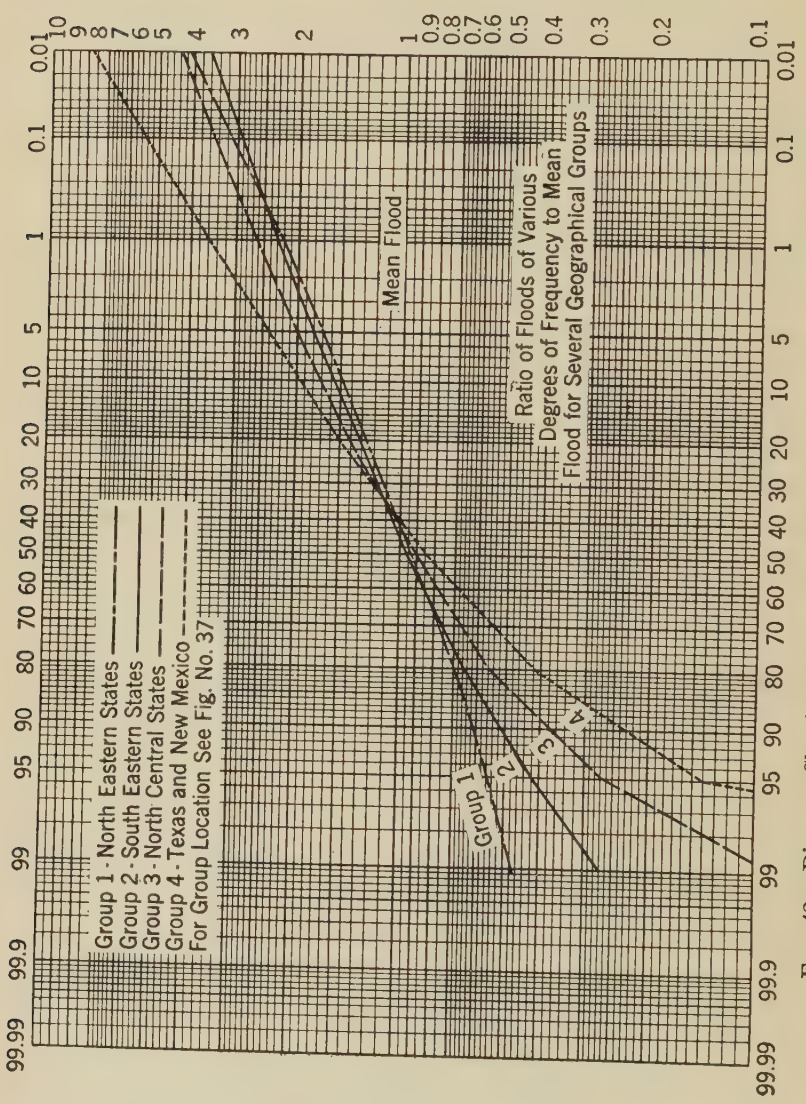
Group 1 - North Eastern States
Group 2 - South Eastern States
Group 3 - North Central States
Group 4 - Texas and New Mexico
For Group Location See Fig. No. 37
Mean Flood
Ratio of Floods of Various Degrees of Frequency to Mean Flood for Several Geographical Groups
Group 1
2
3
4
99.99 99.9 99 95 90 80 70 60 50 40 30 20 10 5 1 0.1 0.01
0.01 0.1 1 5 10 20 30 40 50 60 70 80 90 95 99 99.9 99.99
10 9 8 7 6 5 4 3 2 1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1

FIG. 42.—Diagram Showing Average Flood Ratios Eastern and Southern States.

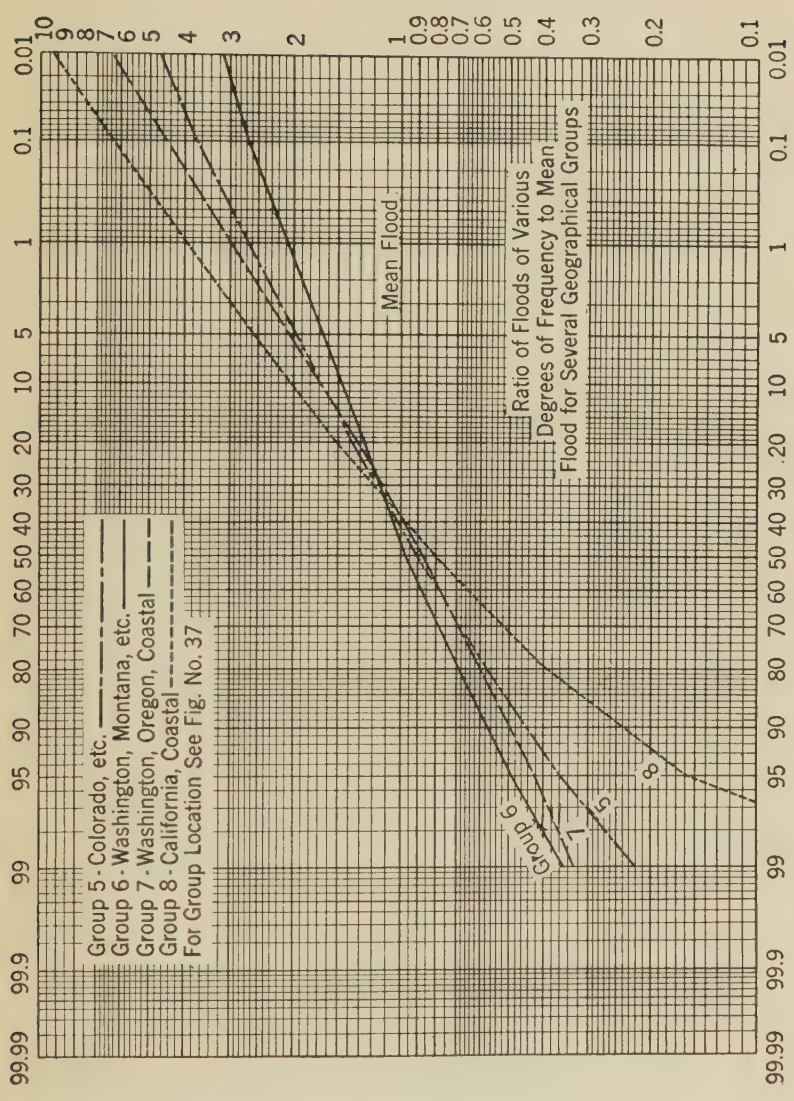
Group 5 - Colorado, etc.
Group 6 - Washington, Montana, etc.
Group 7 - Washington, Oregon, Coastal
Group 8 - California, Coastal
For Group Location See Fig. No. 37
Mean Flood
Ratio of Floods of Various Degrees of Frequency to Mean Flood for Several Geographical Groups
Group 6
7
5
8
99.99 99.9 99 95 90 80 70 60 50 40 30 20 10 5 1 0.1 0.01
10 9 8 7 6 5 4 3 2 1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1

FIG. 43.—Diagram Showing Average Flood Ratios Western States.

These tables bring out some facts not otherwise apparent.

District VII, Washington and Oregon, produces the largest flood flows of any part of the country. California comes next and the Atlantic Coast follows. The northern and southern sections of the latter are so nearly equal in flood-producing capacities that they might have been combined in a single group. The flood quantities for the interior are much smaller and vary among themselves more widely than is indicated by these average figures, each of which represents the mean of an entire geographic group.

These values give no idea of the destructiveness of floods in the different localities because the destruction comes from a flood that exceeds the ordinary by more than a usual amount and that exceeds the flood for which provision has been made. Where the flood quantities are large, as in Oregon and Washington, the river channels presumably are in proportion, and in all cases the rare flood which goes beyond the ordinary and beyond the expectations is the flood that causes damage.

In the above tables only a few values for round quantities are given to illustrate the method of using the data and factors. In case corresponding estimates for intermediate quantities are required, they are easily made by using the same methods. Or the figures given in these tables may be used as plotting points on paper that is logarithmic in both directions. There they will be found to plot as straight lines and from these lines intermediate values may be taken.

An Attempted Analysis of Flood Flows.—The principal causes of great floods in the United States may be classified in a very general way as follows:

(1) Melting snows.
(2) Great storms of wide distribution.
(3) Cloudbursts covering only small areas.

It is true of course that these causes grade into each other and that no lines of demarcation can be drawn; but for the purpose of getting a better idea of the whole situation, let us imagine that the classifications may be carried out in a given case and that the floods of each of the three classes may be separated, assembled, and considered by themselves. The three

classes of floods will then be found to have very different characteristics.

The floods from melting snows will be the most regular and will have the smallest coefficient of variation because the rate of melting depends upon the rise in temperature at a certain season of the year and temperature conditions are in a general way less variable than rain conditions. Plotting these floods by themselves will result in a line that we may assume to be straight or nearly so, and that has a relatively small inclination, as shown on Fig. 44.

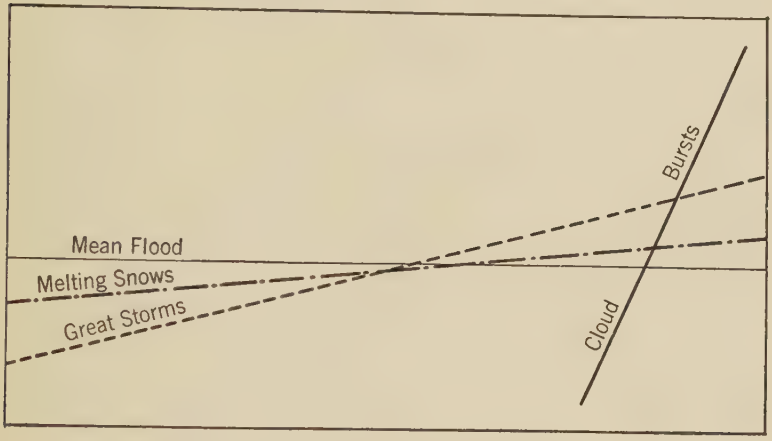

Fig. 44.—Analysis of Causes of Flood Flows.

The floods resulting from great storms will vary much more in size and will therefore be represented by a steeper line on the plotting, but a line, nevertheless, which may be more or less straight.

Floods due to cloudbursts will be of a quite different character. In 99 years out of 100 and perhaps in 999 years out of 1000 there will be no flood that comes in this category, but when such a flood does come it will be big. The line representing such floods plotted separately will therefore be a line with steep inclination and far over at the right-hand side of the diagram, cutting across its end and going down to zero. The whole of the line comes outside of the vertical line representing one per cent of the floods and probably beyond the line representing 0.1 per cent of the floods.

In Fig. 44 are drawn the lines to represent this conception of the three kinds of floods, each considered by itself without respect to the others. No attempt is made to give numerical values to the lines because such values are obviously beyond reach under present conditions.

Looking at the diagram as a whole, with the three lines on it, it is apparent that each line will control where it is above the other two; and that the line showing all of the annual floods will be made up of parts of the three lines, each part being that

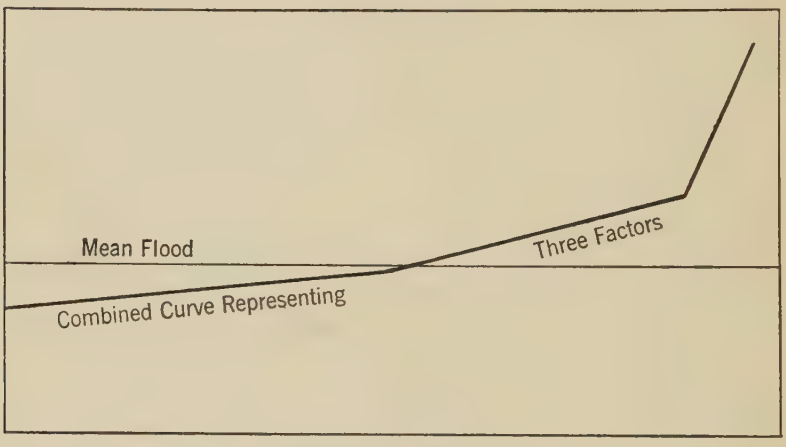

Fig. 45.—Composite Curve of Flood Flows.

line which is above the other two. All the rest of the lines will disappear from the picture.

We can then redraw our curve of annual flood flows as in Fig. 45, which shows the combined curve representing the effect of the three factors. This line is drawn with angles, but actually the corners could be smoothed out, and the lines graded into each other so that a curve in the same general shape would be the result.

We can imagine that the line reached in this way has some sort of a family resemblance in its general curvature to our flood flow lines. The steep inclination far out at the right is rare and in fact does not exist in records of ordinary length. The other parts corresponding to the commoner factors may be approximated in a rough, general way.

Melting snows constitute a flood factor mainly in the north and in streams flowing from high mountains in all parts of the country. Going toward the south, where the climate becomes warmer, they tend to become a smaller factor in flood flows and finally disappear.

Eliminating the part of the line due to floods from melting snows will have an interesting result on the coefficient. Because the average inclination of the line after that part is out is greater, the coefficient of variation will be greater. On the other hand, the curvature of the line will become less and the coefficient of skew will be reduced. These two changes will offset each other with respect to that portion of the line representing the greater and rarer floods, which will remain about the same regardless of this change.

An examination of the three coefficients calculated for Groups I and II, representing respectively the streams of the north and south Atlantic coast, shows that these differences are exactly what are found between the two groups.

There are not enough data with respect to floods from cloudbursts to serve at the present time as a basis for any rational method of representing them on our diagrams, but this procedure gives as fair an idea as is now possible of their significance and relation to the floods caused in other and more common ways.

CHAPTER XII

DURATION CURVE AS A METHOD

By the *duration curve* is meant a curve that shows on the percentage scale the proportion of time in which given limits of flow are exceeded. The curve is frequently drawn to cover the entire range of flows from the lowest to the highest. Duration curves serve a variety of uses in hydraulic calculations and are very commonly made aside from the study of flood flows.

Plotting and Using the Duration Curve.—The duration curve may be plotted on logarithmic probability paper, although it is not to be supposed that the duration curve is a probability curve or will plot as a direct line upon it. In making the plotting, it is better to use the special logarithmic probability paper which has several additional decimal places at one end with a corresponding omission at the other end, the omission not being important from the standpoint of flood flows.

When the duration curve is used for estimating flood flows a few of the highest terms should be plotted individually and with the greatest care to insure that the upper part of the curve is as accurate as it can be made. The positions of these few highest terms should be computed by the method described in Chapter III, taking as the number of terms in the series the whole number of days in the record period.

From the duration curve the ten per cent chance flood may be taken accurately. It will be found at the decimal position corresponding to the reciprocal of the number of days in ten years, namely, at 0.0274 per cent on the probability paper.

Where the upper end of the duration curve approximates a straight line on logarithmic probability paper, it may be extended upward and other flood limits may then be taken from it by extrapolation.

This method is a perfectly good one. There is no reason why the results obtained by it should not be as accurate as those

obtained by the procedure previously described. In a few trial cases they seem to check the results obtained in that way as closely as would be expected by two good independent methods of computation from the same data. The check will naturally be closest for the ten per cent chance flood which comes within the line of the plotting of the actual data. Divergences will commence as the lines are carried by extrapolation away from the actual data and therefore become less certain.

It is apparent that by this method only the records of flow of a rather limited number of days have any appreciable influence on the results that are obtained. Therefore, if no other use is to be made of the duration curve, it will be sufficient to collect a reasonable number of terms at the top, say one or two hundred.

However, the method of selection is important. An arbitrary limit must be set up and all terms above that limit must be included and all those below must be excluded. The terms above the limit may then be classified according to size and plotted, the few highest ones individually and the others as averages of groups of convenient size.

In following this procedure, instead of working on the basis of the whole number of days in the record period, it is possible to arrange the data to show how many times per annum floods above a certain limit occur. The few floods at the top must be expressed as decimals and their positions ascertained, using in this case the formula $P = \frac{2m - 1}{2n}$, where m is the number of terms counted from the top and n the number of years in the series.

Data arranged in this way may be plotted in any one of several ways. Logarithmic paper is perhaps the most convenient, but its use probably leads to excessive estimates for remote floods. At any rate, they are often higher than reached by other methods. Semi-logarithmic paper may also be used. In this case the magnitude of the floods should be represented on the arithmetic scale, and the frequency on the logarithmic scale. A third alternative is to use logarithmic probability paper. In that case it will be convenient to move the figures over two decimal places, putting the flood that occurs on an average once per annum on the one per cent line and others in proportion. This use of

this paper is purely arbitrary and no merit can be attached to it beyond that of convenience.

In following any of these three alternate methods, the plotting will best be made showing the flood quantity in cubic feet per second, because there is no other convenient base to which the numbers may be referred.

All these methods of plotting should check closely for the ten per cent chance flood, and with records of twenty years and over will give results that do not differ widely for the one per cent chance flood. For less frequent floods the estimates will diverge according to the method followed. The results obtained by platting on logarithmic paper usually fall above, and those on semi-logarithmic paper, below, those reached by the use of logarithmic probability paper.

These methods are all purely graphic. There is no computation connected with them and there can be none. The method of selecting the data does not produce results that can be analyzed by such methods as were outlined in the preceding chapters.

The Duration Curve Not a Series Curve.—It is to be recorded that attempts have been made more than once to take these higher numbers, representing the quantities of flood flows above some arbitrary limit, and to treat them as numbers from a series, computing the average and the coefficients of variation and skew, and, using Foster factors, to plot the results found. These methods should not be applied to such data because the numbers selected do not form a proper series. A series of numbers to which such methods may be properly applied should contain either all of the items that there are of a given kind or a fair sample of them. The highest day each year for twenty years may be taken as a sample of the highest days in all the years that there are, that is, of a much longer period of indefinite length. But when floods are selected with reference to their size and without regard to the time of their recurrence, the numbers representing them do not form a series to which probability methods can be expected to apply.

If such data are used there is no use in calculating the coefficient of variation and the coefficient of skew and if these calculations are made, the results mean nothing. Such data should be subjected to graphic methods and graphic methods only.

One of the chief reasons for computing the coefficients of

variation and skew of the annual floods is to secure a definite basis of comparison for the records of different streams. This is one of the principal objects that we are now aiming at, and the use of direct graphic methods does not lend itself to this procedure.

An Example.—As an illustration of these methods, the nineteen-year record of Little River, previously described in Chapter VIII, is taken for further study. The duration curve has been taken off, the limits being stated in terms of ratios to the mean flow. This is plotted in the upper part of Fig. 46. The line representing daily flows is extended and estimates of various floods are obtained from the extension. The figures taken from the diagram are multiplied by the mean flow of stream and converted from mgd. (million gallons daily) to cfs. units to produce the required estimates.

From this same record one hundred or more of the highest flood flows have been taken out, regardless of the years in which they occur, with results as shown in the following table:

THE LARGEST ONE DAY FLOODS IN A NINETEEN-YEAR RECORD OF LITTLE RIVER IN THE ORDER OF SIZE AND WITHOUT REGARD TO THE TIME OF THEIR OCCURRENCE

Individual floods—cfs.	Lower limits of flood groups—cfs.	Number of floods above limit	Number of floods per year
3793	.....	0.5	0.026
2987	.....	1.5	0.079
2317	.....	2.5	0.132
1938	.....	3.5	0.184
1844	.....	4.5	0.236
1590	.....	5.5	0.289
	1392	10	0.527
	1237	16	0.840
	1083	20	1.05
	928	28	1.47
	773	52	2.74
	619	102	5.38

These results have been plotted in each of the three ways described in the lower part of Figs. 46 and in 47.

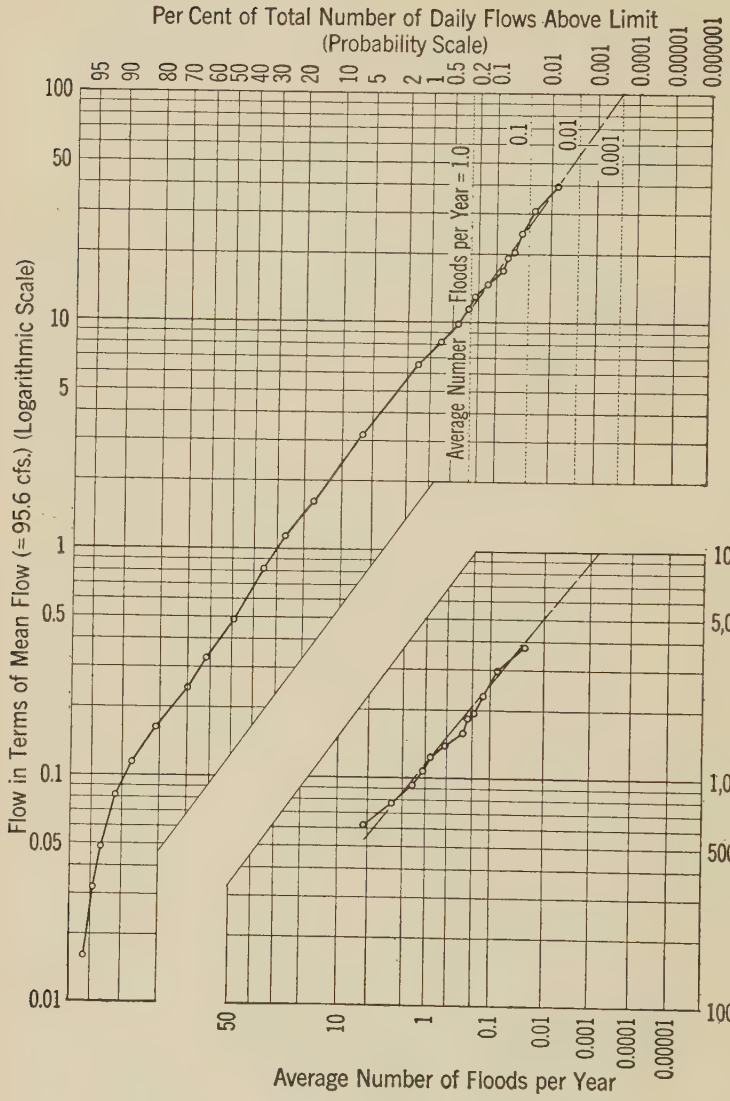
Per Cent of Total Number of Daily Flows Above Limit
(Probability Scale)
95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01 0.001 0.0001 0.00001
100 50 10 5 1 0.5 0.1 0.05 0.01
Flow in Terms of Mean Flow (=95.6 cfs.) (Logarithmic Scale)
Average Number Floods per Year = 1.0
0.1 0.01 0.001
10,000 5,000 1,000 500 100
Flood Limit cfs. (Logarithmic Scale)
50 10 1 0.1 0.01 0.001 0.0001 0.00001
Average Number of Floods per Year

FIG. 46.—Upper: Duration Curve by Days. Lower: Number of Times per Annum.

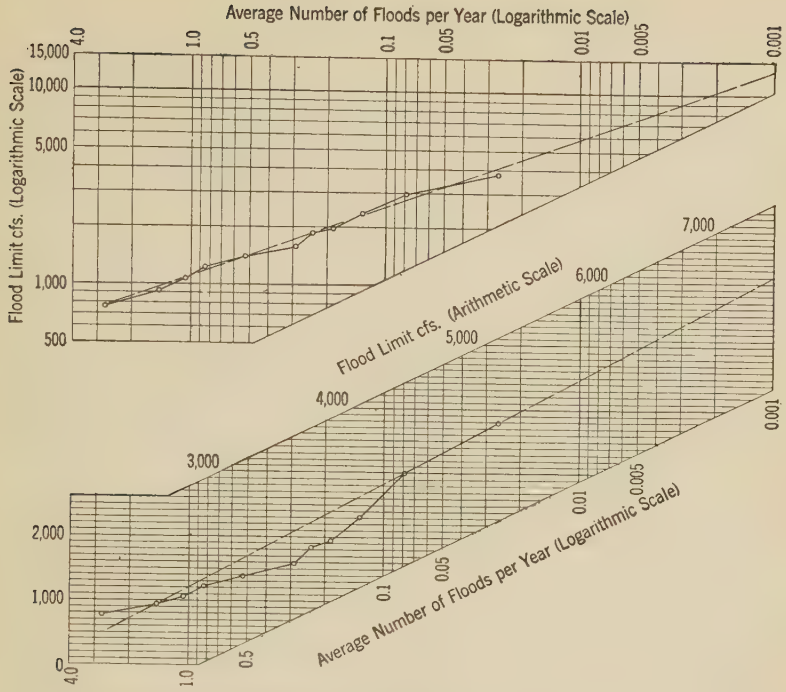

FIG. 47.—Number of Floods per Annum. Upper: Logarithmic. Lower: Semi-logarithmic.

The following is a tabular statement of the estimated flood limits computed from these identical data by the different methods of plotting, and there are also shown the corresponding

RESULTS OBTAINED BY USING DIFFERENT METHODS IN DATA FROM LITTLE RIVER FOR NINETEEN YEARS ENDING 1928

Chances of occurrence of flood above limit in any one year, per cent	Procedure of maximum annual flood, Chapter VII	Duration curve method plotted			
		Full duration curve	Modified log. prob. method	Log. log. paper	Log. arith. paper
10	2440	2580	2600	2500	2800
1	5000	5300	5100	5800	4480
0.1	8850	10000	9000	13400	6100

estimates obtained by using the ratios obtained by the processes of the earlier chapters as carried out and as shown in Fig. 7.

No special significance is attached in this case to the discrepancies between the values estimated by the different methods of plotting. A number of such comparisons would need to be made before any general conclusions as to the reliability of the different procedures could be safely drawn.

It is hoped that this brief statement will suffice to give an idea of the nature of the procedures and of certain variations in them.

Plotting Gage Heights.—There is another method of studying flood flows in one locality that has considerable merit. It was alluded to in Chapter II. It consists in plotting the gage heights instead of the water quantities.

The methods to be used in plotting gage heights will follow that of plotting water quantities so closely that no special instructions need be given. Arithmetic probability paper will usually be best for this service because the skew in the curve showing gage heights is less than the skew in the water quantities of the same stream and record period. The skew is less in the gage height record because, as the water quantities increase, gage heights usually increase in decreasing ratio. This may not always be the case, but it seems generally to be true.

Two examples of plottings of gage heights are given:

(1) The gage heights of the Ohio River at Cincinnati, reproduced from the author's discussion of Mr. Fuller's paper on Flood Flow[1] in Fig. 48.

(2) The gage heights of the Connecticut River, at Hartford, during an eighty-four-year record period, from data of Colonel Pillsbury and Major Skinner in Fig. 49.

These are both plotted on arithmetic probability paper and are well represented by straight lines. There is hardly any skew. They give clear and convincing ideas of the chances of still higher floods occurring in these two localities.

Data of this kind are not susceptible of being brought into a general discussion, because there is no general comparison that can

[1] Transactions Am. Soc. C. E., Vol. 77 (1914), p. 631.

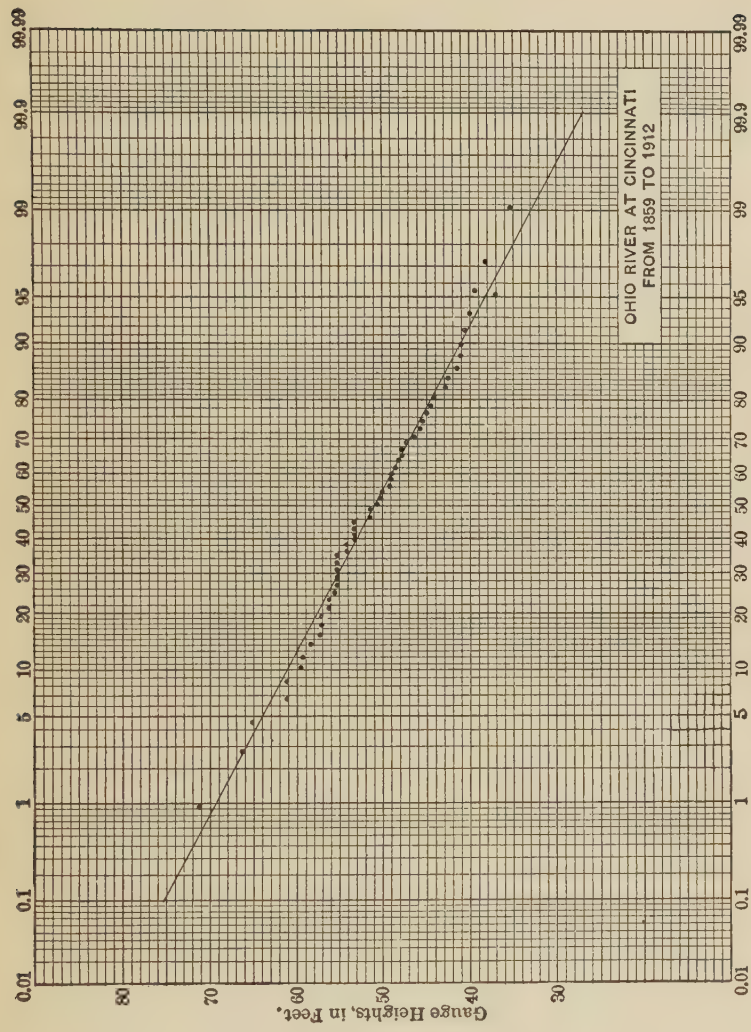

FIG. 48.—Gauge Heights at Cincinnati, from Transactions American Society Civil Engineers, Vol. 74, p. 631, 1914. This Plotting is Reversed as Compared with Fig. 49. The Plotting May Be Made Either Way on Logarithmic Paper without Difference in the Results.

be made between the gage heights and water quantities in different places. In any particular case, where the data are available, as they often are, it is one of the most useful methods of considering what levels must be contemplated in flood protection work.

In using gage heights one must always bear in mind that changes in the channel below may be made by man, who may either enlarge it and improve it with reference to navigation or the free flow of flood quantities, or obstruct it by bridges, buildings and all sorts of works. As far as these changes come into play, they tend to reduce the value of this procedure.

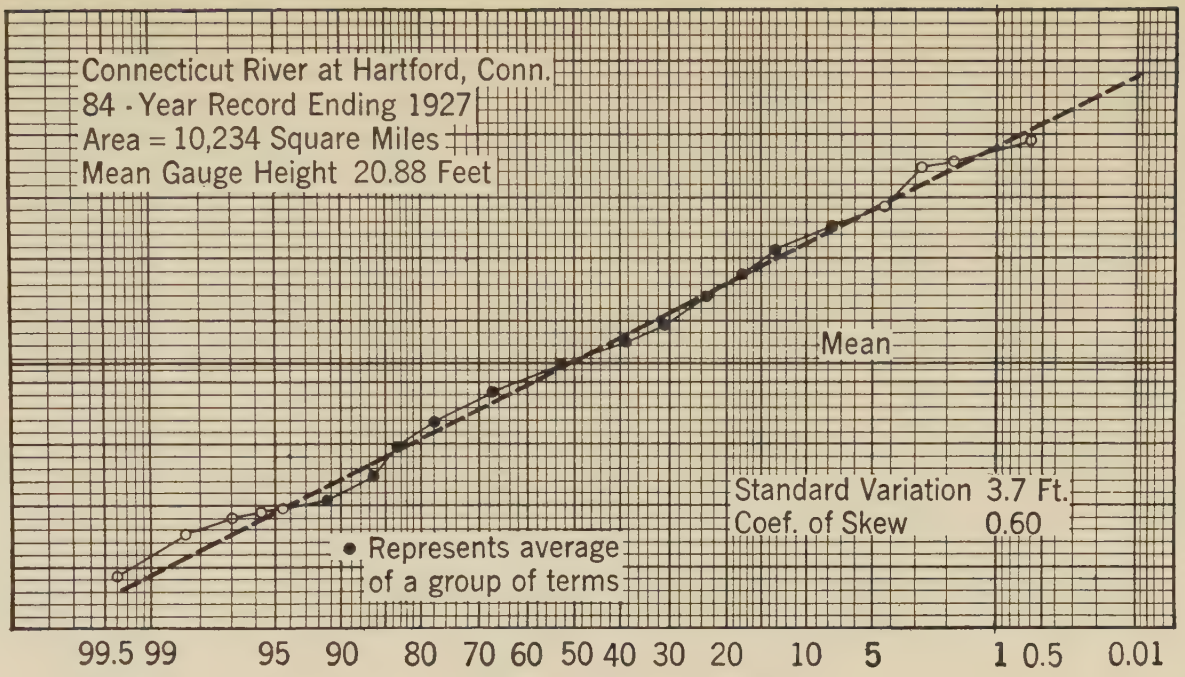
Connecticut River at Hartford, Conn.
84 - Year Record Ending 1927
Area = 10,234 Square Miles
Mean Gauge Height 20.88 Feet
Mean
Standard Variation 3.7 Ft.
Coef. of Skew 0.60
• Represents average of a group of terms
Gauge Height in Feet
30
25
20
15
99.5 99 95 90 80 70 60 50 40 30 20 10 5 1 0.5 0.01

FIG. 49.—Gage Heights at Hartford.

CHAPTER XIII

THE EXTREME-FLOOD METHOD

Extreme-Flood Data.—Emil Kuichling collected in a most painstaking way and published records of a great many extreme floods which could be used for comparison and as an aid in forming judgment as to flood quantities to be provided for in engineering works. This was first published in the New York State Engineers' Report on the Barge Canal in 1901, p. 844. A supplement was presented as a discussion of Mr. Fuller's paper in 1914.[1] Since then a number of such lists have been prepared by engineers in a more or less similar manner, but not always covering as broad a field.

Among these lists may be mentioned one by H. P. Eddy, Transactions Am. Soc. C. E., Vol. 85 (1922), p. 1528, and one by Joel D. Justin, Transactions Am. Soc. C. E., Vol. 87 (1924), p. 135. There is also a list by Gardner S. Williams in the section on Water Power in the American Civil Engineer's Handbook. The most recent and extensive of the tables of this description is one presented by C. S. Jarvis in a paper in the Transactions Am. Soc. C. E., Vol. 89 (1926), p. 985. Mr. Jarvis received a prize for this paper. It is very comprehensive and covers nearly a thousand flood records.

Kuichling, Jarvis and others have studied these results by plotting them upon logarithmic paper showing the discharges, or, better, the discharges per square mile against the catchment areas, and by drawing lines to include most of the points but not all of them.

Kuichling drew one line for floods that occurred frequently and one for floods that occurred rarely and prepared formulas to represent these lines. Similar lines and formulas have been prepared by other engineers to represent particular problems or the data from particular localities.

[1] Transactions Am. Soc. C. E., Vol. 77 (1914), p. 650.

It should be noted that all of these data represent maximum floods; that is, the maximum rate of discharge for any short interval of time. One-day floods are not used and do not enter the picture in any way. This distinction must be kept always in mind because it makes a difference that is important and that is greatest for small areas. This point is easily overlooked.

The length of time in the record period is another matter that does not enter this picture. Many of the items of data shown in these tables—probably most of them—relate to isolated floods on streams that are not ordinarily gaged. In such cases estimates of flood flow have been made afterward. There is no basis for comparing them with the mean flood of the same stream. The best we can do is to make an estimate of the mean flood for such comparison. This is not a very satisfactory procedure, but it is the best that can be done.

In using these records, it must be borne in mind that most of them are not very accurate and a certain percentage of wholly erroneous results is to be anticipated.

This general method of estimating floods has been useful. When Mr. Kuichling first proposed it twenty-eight years ago, it was no doubt the most promising if not the only method then available for solving the problems with which he was dealing. The method is not to be discarded even now, for it may still prove to be the best method of procedure in regions where local data are scattered and not continuous. It also serves as a basis for checking estimates.

Use of the Extreme-Flood Method.—There is an important service which these records may render and that is to furnish a general comparison with estimates of probable maximum floods based on the records of gagings. This is a new and entirely different angle of approach and it is important to see how the results compare.

A rapid preliminary study was made of the highest relative values in the above mentioned tables of floods and a few of the highest were taken for further study. This study was limited to two groups, one covering the northeastern states as far south as Maryland, and the second covering the Ohio floods which have been studied in the Miami Reports in more detail than any other corresponding floods. Some very extraordinary floods reported from areas of less than one square mile have not been

included. They may represent extreme cases of a condition of which the items in the table for larger areas are examples.

Records for use in this table were selected by finding those that had more than a certain ratio to a rather arbitrary estimate for a one per cent chance flood for the same area. The records with the comparison are shown in the following table:

Stream	Year	Area	Quantity in 1000 cu. ft. per second		Ratio, actual to estimated	Authority
			Actual	Estimated by A. H.		
Northeastern						
Chester Cr., Pa.	1843	62	62	8	7.75	Hauk, ENR 89, 402
Mad Cr., N. Y.	1916	1.5	3.45	0.7	4.90	Justin, ASCE 87, 135
Mill Cr., Pa.	1915	12.9	12.9	2.75	4.70	Gannet, E News 74, 937
Indian Run, Pa.	1911	2.1	4.05	0.88	4.60	Justin, ASCE 87, 135
Darby Cr., Pa.	1843	48	28	6.7	4.17	Hauk, ENR 89, 402
Ridley Cr., Pa.	1843	20	15	3.6	4.17	Hauk, ENR 89, 402
Canodochly, Pa.	1914	2.2	3.6	0.9	4.00	Justin, ASCE 87, 135
Green Br., Pa.	1914	1.7	2.7	0.76	3.55	Water Sup. Com. Pa.
Crum Cr. Pa.	1843	22	9	3.95	2.28	Hauk, ENR 89, 402
Westfield, Mass.	1878	356	53	27.3	1.95	H. F. Mills, Sp. Rep.
Esopus, N. Y.	1924	192	32.8	17.5	1.86	Honnes, ASCE 89, 1042
Esopus, N. Y.	1878	417	55	30.5	1.81	Fuller, ASCE 77, 614
Brush Cr., Pa.	1903	6	3	1.7	1.77	Pa. Water Com. Rep. 1912
Schuylkill, Pa.	1850	900	90	53	1.70	Miami Reports
Susquehanna, Pa.	1889	5670	350	211	1.66	Miami Reports
Deerfield, Mass.	1915	332	41.7	26	1.61	U. S. G. S. Supply Data
Burgoons Run, Pa.	1889	8.1	3.2	2.0	1.60	Pa. Water Com. Rep. 1912
Lake Roland, Md.	1868	39	9	5.8	1.55	Fuller ASCE 77, p. 614
Johnstown Flood, Pa.	1889	48.6	10	6.8	1.47	Com. Report ASCE, Vol. 24, 431.
Ohio						
E. Br. Honey Cr., O.	1918	6.7	14.85	1.8	8.35	Hauk, ENR 87, 480
E. Fork Honey Cr., O.	1918	11.8	15.2	2.6	5.85	Hauk, ENR 87, 480
Lost Cr.	1913	52	29.7	7.05	4.22	Hauk, Miami R. IV, 60
Twin Cr.	1913	270	66	22.3	2.96	Hauk, Miami R. IV, 60
Miami, at W. Miami	1913	2937	384	162	2.36	Hauk, Miami R. IV, 60
Still Water R., W. Milton	1913	611	86.2	40.5	2.14	Hauk, Miami R. IV, 60
Ludlow Cr. above Falls	1913	65	17.3	8.2	2.10	Hauk, Miami R. IV, 60
Miami R., Miamisburg	1913	2722	257	122	2.10	Hauk, Miami R. IV, 60
Miami R., Tadmor	1913	1128	127.3	63	2.02	Hauk, Miami R. IV, 60
Stillwater R., below L. York	1913	657	85.4	42.5	2.01	Hauk, Miami R. IV, 60
Mad. R., Osborne	1913	649	75.7	42	1.80	Hauk, Miami R. IV, 60
Tawawa Cr. East of Sydney	1913	54	12.9	7.2	1.79	Hauk, Miami R. IV, 60
Still Water, above Greenville	1913	223	33.1	19.5	1.70	Hauk, Miami R. IV, 60
Still Water at Sugar Gro.	1913	448	51.4	32	1.61	Hauk, Miami R. IV, 60
Mad. R., at Springfield	1913	505	55.4	35.0	1.58	Hauk, Miami R. IV, 60

Ivan E. Hauk has been the most important contributor to these data relating to extreme floods and he deserves special credit for collecting and publishing his data. His articles in Engineering News-Record on the flood of Honey Creek in Ohio,[2] and on an unusual flood in Delaware County in Pennsylvania eighty years ago,[3] should be most carefully read in full by all who would master this subject. In Part VI of the Miami Report he describes at length the methods and results of estimating the flows in the great floods of 1913 in and near Dayton, Ohio.

The other records that have been selected have been followed back to the original publication as far as practicable, and in the above table the earliest reference is given in each case, as far as found. No convincing story of original authority is available in several cases. A few items inconsistent with published records of gagings have been excluded. A few notes are presented on some of these floods.

The Johnstown Flood was investigated by a committee of the American Society of Civil Engineers.[4] The members of the committee, J. B. Francis, W. E. Worthen, A. J. Becker, and A. Fteley, estimated the maximum rate of discharge above the dam whose break was the direct object of the report.

The estimate of the flood at Lake Roland, a part of the Baltimore Water Supply, attributed first to Mr. Fuller and then to several of the other gentlemen who have prepared flood-flow tables, brings back interesting memories. The author visited this source of supply in 1909 and found the old keeper on the ground who showed the marks of high water at the time of the Johnstown flood twenty years before. This flood passed over the dam without breaking it, but caused some erosion at one end. The dimensions were secured and a computation made of the discharge, which was entered by the present author in his list of notable floods. Notwithstanding some uncertainty as to the effect of erosion at the ends of the dam on the discharge, the estimate is believed to be as accurate as others in this list. W. E. Fuller, then the author's partner, used this list in writing his paper on Flood Flows.[5]

The great flood of 1868 on the Westfield River, in Massa-

[2] Engineering News-Record, Vol. 87 (1921), p. 480.
[3] Engineering News-Record, Vol. 89 (1922), p. 402.
[4] Transactions Am. Soc. C. E., Vol. 24 (1889), p. 431.
[5] Transactions Am. Soc. C. E., Vol. 77 (1914), p. 564.

chusetts, is not to be found in some of the flood lists, but it was a notable flood and the estimate of discharge was made by Hiram F. Mills, afterwards for many years hydraulic engineer of the Lawrence and Lowell water power companies and as competent as any man in the country to make this difficult estimate.

In general it may be said that the records in these lists were based on such data as could be collected after the event. In some cases the estimates were made long afterward. In all cases they must be regarded as rough approximations only. Mr. Hauk speaks of this in one of his articles. The records are none the less valuable to us notwithstanding the inevitable lack of precision in the results.

Most of these records depend upon estimates made by applying Kutter's formula to channel conditions, but in the Miami floods Mr. Hauk used, where conditions permitted, a method suggested to him by Prof. S. H. Woodward based upon the loss of head in passing contractions in the channels. In other words, it was based on something not unlike the principle of the Venturi meter.

In selecting these data, items were entered which were more than fifty per cent in excess of a figure which might reasonably be estimated for a maximum one per cent chance flood flow from that area. In estimating the maximum one per cent chance flood for this use, no account was taken of the variations in flood coefficient for the different streams, but a single calculation was made with a flood coefficient of 80 which may be accepted as not far from an average for all the streams that are represented. It is higher than the average for Group I, but taking into account the character of the streams which have contributed to these maximum floods, many of which came from the mountainous part of Pennsylvania, it is not too high. Many of the records come from Ohio and there is no evidence in the data at hand as to what the normal flood coefficient for these Ohio streams may be. In this procedure the same value of the coefficient was used for these Ohio streams as for the others.

The mean flood estimated in this way is multiplied by 2.26 to find the one per cent chance flood. The figure so found is further multiplied by the factor in Fuller's formula for the maximum flood as compared with the one-day flood. These calculations were made by approximate and partly graphic methods,

and only the results are entered in the table. Finally the ratio of the reported flood to the estimated one per cent chance maximum flood is shown.

We must remember that the coefficient of flood taken at 80 in all cases may actually be 100 or more in some cases, and this would represent a possible increase of 25 per cent in the estimate. A 0.1 per cent chance flood for the Group I is normally 36 per cent greater than a one per cent chance flood, and there were probably some such floods in the list. These two possible additions are cumulative and should both occur together they would add 70 per cent to the estimate. It is apparent that there is no occasion for special investigation of values that do not exceed the estimated flood by more than fifty per cent.

It is not to be supposed that this short table of extreme flood values represents all the floods in this region. Mr. Hauk by his efforts for the Miami Conservancy Commission and in other ways has contributed more than half of the entire list. If there had been a number of engineers of Mr. Hauk's energy and care distributed throughout the area for the last eighty years, it is certain that the list would have been much longer.

Probably a number of values from the Vermont floods of 1927 would be included in the first part of the table if authentic estimates of the floods were available at this time.

In addition, there were, no doubt, innumerable similar floods in wild areas that did no damage and attracted no attention.

Nevertheless, the total area represented by all these records is a very small proportion of the total area of the states which are represented in the table. It is certain that these data are, to some extent, representative of the highest flood rates of flow in this area for the last eighty years. *Most of the areas in the states represented have not had such large floods in such a period of years.*

Although no accurate rating can be assigned to them it seems certain that these floods are of the rare class, probably many of them greater than 0.1 per cent chance per annum and some of them as great as 0.01 per cent chance per annum. A 0.01 per cent chance flood, according to the figures for Group I on the logarithmic probability curve, will be 75 per cent larger than a one per cent chance flood. To this there is the possible addition from a larger flood coefficient as noted above.

We may say, then, that the values in the table up to a ratio of about two may be accepted as coming within the range of that which is not surprising from the standpoint of the study of probability flows that has been presented in the preceding chapters. All of the floods from the larger rivers, except the Miami, come within this limit. The Miami goes a little beyond it, but we must remember that we have no data for Ohio to establish what the normal flood coefficient is.

There remain a considerable number of floods from small areas which have much higher flood ratios, going up in cases to about eight times the estimated values for one per cent chance floods. These cannot be accounted for by the methods used in the preceding chapters even on the theory that they are extraordinarily rare floods.

To test this out a little further, we may compute for Chester Creek, the flood record of which may be taken as perhaps the highest relatively in the whole list, the values of the 0.01 per cent chance flood. First, we use the three coefficients which are the average for Group I, and afterwards the coefficient found separately for three streams which are not very far from Chester Creek and which may be appropriately compared with it, namely, Perkiomen, Neshaminy, and Tohican Creeks, which were gaged for twenty-nine years by the Philadelphia Water Department.

Using the Fuller factors for the maximum rates of flow, the results may be stated in tabular form:

Basis of estimate	Quantity, cubic feet per second	Ratio of actual flow to estimate
Chester Creek actual flow.....	62,000	
Estimated from average of Group 1....	12,000	5.15
Estimated from Perkiomen Creek data.	9,400	6.60
Estimated from Neshaminy Creek data.	18,000	3.45
Estimated from the Tohicken Creek data.	17,300	3.60

It is apparent that the actual quantity was far above any estimate. It is to be remembered that the quantity could not be determined closely. Mr. Hauk, who made the estimate, says in regard to it:

> Although the above values are somewhat uncertain, it does not seem likely that they are as much as fifty per cent in error. It is believed that

such errors as do exist are negative rather than positive; that is, that the values given are too small rather than too large. It is to be regretted that the runoff rates cannot be determined more accurately; but, considering the unusual magnitude of the floods, it is believed that the above data are worthy of presentation.

Making all allowance for errors in this and in other high records, there is no question but that there have been a few enormously high rates of runoff from small areas that do not apparently fall in line with the methods of estimating floods that have been presented. These extreme rates have apparently all come from very heavy thunder storms. They might possibly be explained by some change in the formula applicable to small areas, or by some change in the form of the skew curve that would throw the line as much above the logarithmic probability curve as the Foster Type III falls below it.

What May be Learned from these Studies.—Sometime this matter will all be cleared up with an explanation that may then seem ridiculously simple, but, at present, the data are too few and too scattered to offer promise of early solution. This is one of the problems that must be left for more data and further study.

No effort has been made to arrange and study the data from other parts of the country in a similar way. The difficulty of the procedure in the West would be greater because local conditions are less homogeneous from one stream to the next. In the case above cited, the three carefully gaged creeks afford a basis that seems to be unusually good for comparison with the extremely high observed flow on Chester Creek, but throughout all the great regions from the Rocky Mountains to the Pacific Coast, except Washington and Oregon, the greatest varieties in local conditions are found within short distances. There may be cases where neighboring areas have been completely gaged, and are available, so to speak, pace-maker for extreme flood records. If so, the cases would be unusual, and the data would have to be selected with the greatest care and with full knowledge of local conditions.

The lessons to be learned at the moment are:

(1) That for spillways and structures where damage would result from having the capacity overtaxed,

liberal allowances must be made to cover extreme conditions that may possibly happen sometime but that are unlikely ever to happen in any given case.

(2) In considering the form of curve to be adopted to represent flood flows of different degrees of rarity and especially in deciding between Foster's Type III and the logarithmic probability procedure, these data point toward using that form of curve which gives the higher estimate for extreme values.

CHAPTER XIV

SEASONAL DISTRIBUTION OF FLOOD FLOWS; AND LOCAL AND OTHER FACTORS

Seasonal Distribution of Flood Flows.—In any climate there is a greater chance of floods at some seasons of the year than at others. In some climates one can be sure that there will be no floods during certain months whereas in others a flood must be expected during any month but great floods are more likely to occur at certain seasons.

In the Atlantic states, both north and south, the greatest floods normally occur in the late winter and early spring, but there is another flood period in the autumn. Sometimes there are great floods at other seasons but these are less frequent.

Melting snows in the mountains and northern forests are an element in causing the winter and spring floods. Melting snow usually produces a flood of rather long duration and free from extreme peaks. The autumn floods, when they come, are more apt to go up to an extreme rate of flow for a short time.

In much of California great floods may be expected only in the rainy season, and there are places where the maximum flood of the year may represent a not inconsiderable percentage of the total annual runoff. On the other hand, the streams coming from the Sierras have their greatest floods in early summer, caused by the rapidly melting snows on the high mountains. The same conditions prevail on many streams in the interior whose chief source of supply is in the high mountains that collect snow in winter and give it up as the season advances.

An idea of the seasonal distribution of floods is presented in Figs. 50 and 51, prepared to represent the seasonal distribution of flow of two streams. These are the Little River being the water supply of Springfield, Mass., with a catchment area of 48 square miles of steep, almost mountainous country; and the Susquehanna River at Harrisburg, one of the largest rivers in

the east, with a catchment area of 23,885 square miles, that is also hilly and mountainous.

These diagrams have been prepared by making duration

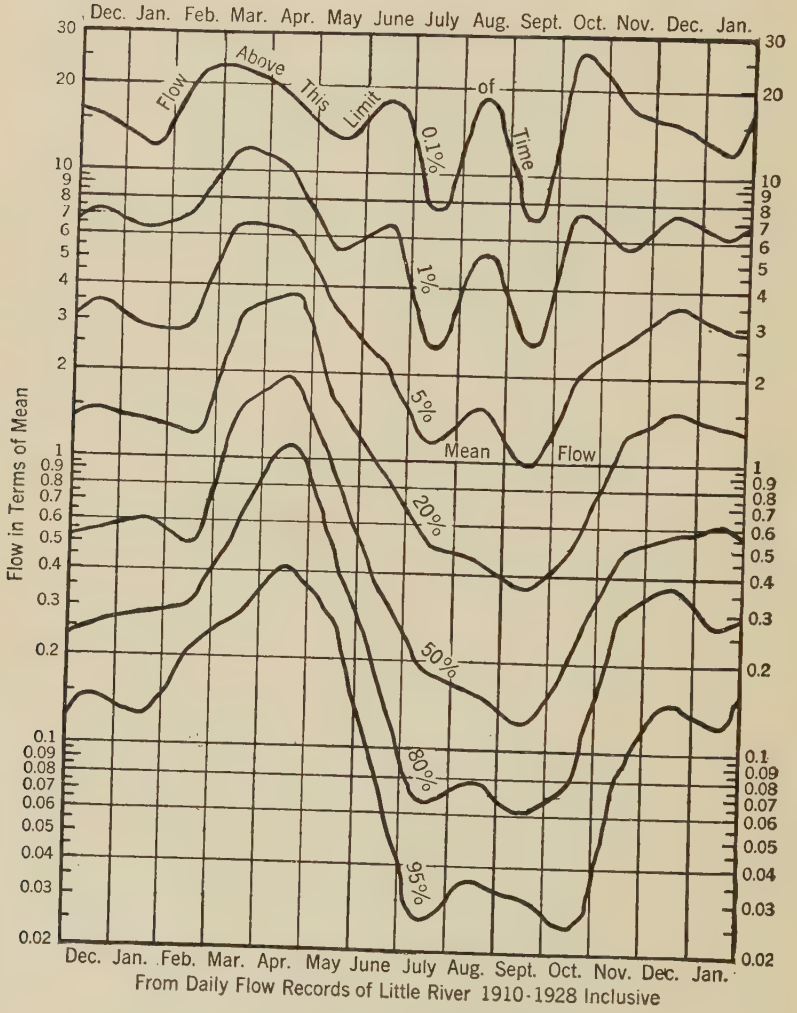

FIG. 50.—Seasonal Flows of Little River.

curves for all the flows of each stream for each of the twelve months in the year. All of the Januarys have been consolidated into a single record and each of the other months has been

treated in the same way. Values taken from these are again plotted on diagrams which show the relative frequency of occurrence of flows of various magnitudes throughout the year. These

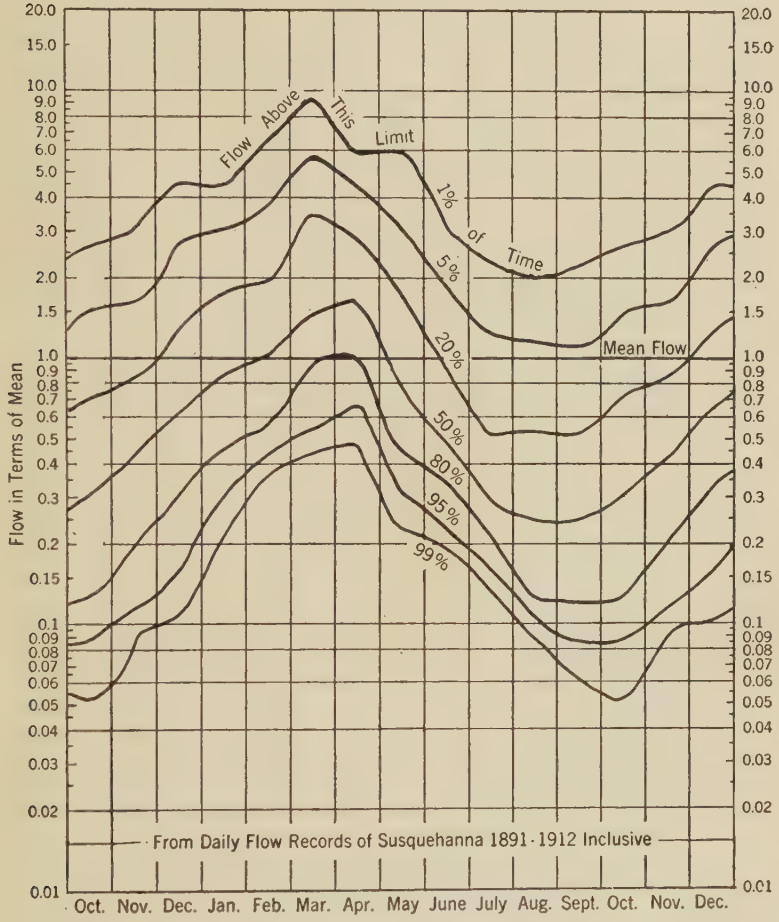

FIG. 51.—Seasonal Flows of Susquehanna River.

plottings as drawn extend over more than twelve months, a part of the record being plotted twice. This is done to show the whole winter flow together without separating at the end of the calendar year.

The basis used in making these plottings is the mean annual flow of each stream for the entire record period. The rates of

flow are all expressed in ratios to this mean and the two diagrams are thus directly comparable with each other.

The method of procedure followed in making the diagrams may be briefly outlined, although it will not be necessary to reproduce the whole calculation and the intermediate plottings.

The record of daily flow is first classified by cutting it up into groups between arbitrary limits, each limit being ordinarily from one and a half to two times that of the one below. In the case of the Little River, for instance, the limits were 1 mgd, 2–3–5–7–10–15–20–30–50–70–100–150–200–300–400 mgd. The larger numbers representing a few of the greatest flood flows were dealt with separately.

The number of terms between limits was taken off for each month in the nineteen-year series, and the monthly results were combined, nineteen Januarys, nineteen Februarys, etc. These results might be plotted directly on their quantities, but it is more convenient to handle data of this kind in proportion to the mean flow and this procedure was followed in this case.

The ratio of each of the limits to the mean flow, which for this nineteen-year period was 61.8 mgd., was ascertained. From the results thus assembled a duration curve was plotted for the entire year and similar curves for the Januarys, Februarys, etc., making twelve curves in all. From these curves the proportions of days above the various limits were taken and these were used in plotting the lines showing seasonal variation. The lines for the different months were plotted first in straight lines and then curves were drawn, the line in the space representing each month being kept at the average value for that month.

The variations in flow as shown by the curves for the Little River are greater relatively than for the Susquehanna. The Susquehanna is five hundred times as large as Little River and fluctuations are greater for smaller streams. The positions of the spring and fall peaks for the two streams occur at exactly the same season of the year and give no indication of appreciable variation of the climate between the two areas.

The diagrams, especially the one for Little River, show that the months that have the smallest ordinary flows have much greater relative variations between dry and wet times than the months that have higher ordinary flows. April has the highest ordinary flow and the smallest normal relative variation between

high and low quantities. October is normally one of the dry months but the range between high and low quantities is greater for October than for any other month. This means that the largest flood flows are more evenly distributed throughout the year than is the case with the ordinary flows or with the smaller floods that occur frequently. Any month in the twelve may sometimes produce a great flood, and the dry months of the summer and fall are greater contributors in the long run to such floods than the first inspection of the diagrams would indicate.

These diagrams may be used as a guide in indicating the probable seasonal distribution of stream flows through a fairly wide strip of northeastern country of which they may be taken as representative.

Similar diagrams have sometimes been made for other local data as, for instance, in California, and they will frequently be found helpful in solving local problems.

Other Flood Periods.—The study so far has dealt entirely with the maximum one-day floods. It frequently happens that estimates must be made for other periods. If there is no storage and the flood flows must be passed as they come, the absolute peak will be controlling. This is the condition that must be met in a small way in the design of storm sewers and other similar drainage works where there is and can be no storage of flood waters during the flood period.

In the case of the spillway for a reservoir there is normally a certain amount of freeboard storage that will tend to distribute and reduce short-time peaks. That is to say, the water in the reservoir will rise temporarily against the freeboard or that part of the dam above the normal flow line. If the reservoir is large this freeboard storage may be sufficient to absorb the whole of the peak above the one-day average flow, and, if so, there is no need of carrying the study further.

If the freeboard storage is not enough for this purpose, it will still absorb a certain amount of it, and the flow for some shorter period than twenty-four hours, but not the extreme peak, will be controlling. It will then be important to estimate how much the rate for such shorter period will exceed the average one-day flow; and the estimate must then be made accordingly.

It is possible to answer questions of this kind in particular cases where the record is made up from the indications of an automatic recording apparatus from which the rate of flow for each minute of the twenty-four hours may be determined. There are also a certain number of cases where records of flow have been obtained by methods that permit the curve of the flood volume to be plotted by hours with a fair degree of accuracy, as, for instance, where measurements over a dam have been taken at frequent intervals during the course of a great flood. Although data of this kind are numerous, they are not usually readily available and the methods have not been sufficiently developed to permit safe generalizations to be made in this field at the present time.

Weston E. Fuller, in his paper on Flood Flows,[1] collected twenty-six ratios representing the entire size range from one square mile to the largest rivers. The data were mainly for the eastern streams with a few items from the interior and none from the Pacific slope. He plotted the results and deduced the following formula to be used in estimating:

$$Q_{\max} = Q_{24\text{ hr.}}\left(1 + \frac{2}{A^{0.3}}\right).$$

The values of the factor to use in multiplying by the twenty-four-hour flood for a number of areas, are:

Area, square miles	Factor
1	3.0
10	2.0
100	1.5
1,000	1.25
10,000	1.126
100,000	1.063

A more complete table of the factors is presented in Table VI of the Appendix. These factors may be used as a rough preliminary

[1] Transactions Am. Soc. C. E., Vol. 77 (1914), p. 564.

guide for eastern streams, but it will not do to assume that they apply closely, because actual results scatter and vary quite widely in individual cases.

Only a few items will now be added to Mr. Fuller's collection.

The data for the Little River at Springfield were taken off in considerable detail for the eleven-year period ending in 1920. They are here shown, not because of any importance as general data but as an example of what can be done where automatic gaging equipment gives a continuous record of stream flow.

The records of each of the eleven years were examined for the highest rate of flow for one hour, three hours, etc. These values were tabulated. In doing this it was necessary to go through the records in considerable detail because it is not at once apparent from inspection just where the highest rate for any short period will be found. The record must be gone through, all high flows taken off, and many trials made and items rejected before the one that is highest in each class can be established.

It was found in this record that the highest one-hour rate of flow would not always occur on the same date as the maximum twenty-four-hour flow. In fact, there was considerable variation in the dates when the highest flows in the different classes were found. In such cases the highest record of its class in any one year is used, regardless of the time of its occurrence.

The eleven highest records found for each length of time, one for each year, were plotted on logarithmic probability paper in Fig. 52, and values for a normal ten per cent chance flood were obtained from the plotting so made. The periods of time considered ranged from one hour to thirty days. The extreme maximum rate of flow in this case was not appreciably greater than the one-hour average rate. The Fuller factor is 1.62, and agrees well with this record as noted in the table presented here.

The results for a ten per cent chance flood are shown in the table on page 133.

As the lines in the plotting run nearly parallel, the ratios to be expected for the normal one per cent chance flood and floods of other degrees of probability would not differ widely from those shown.

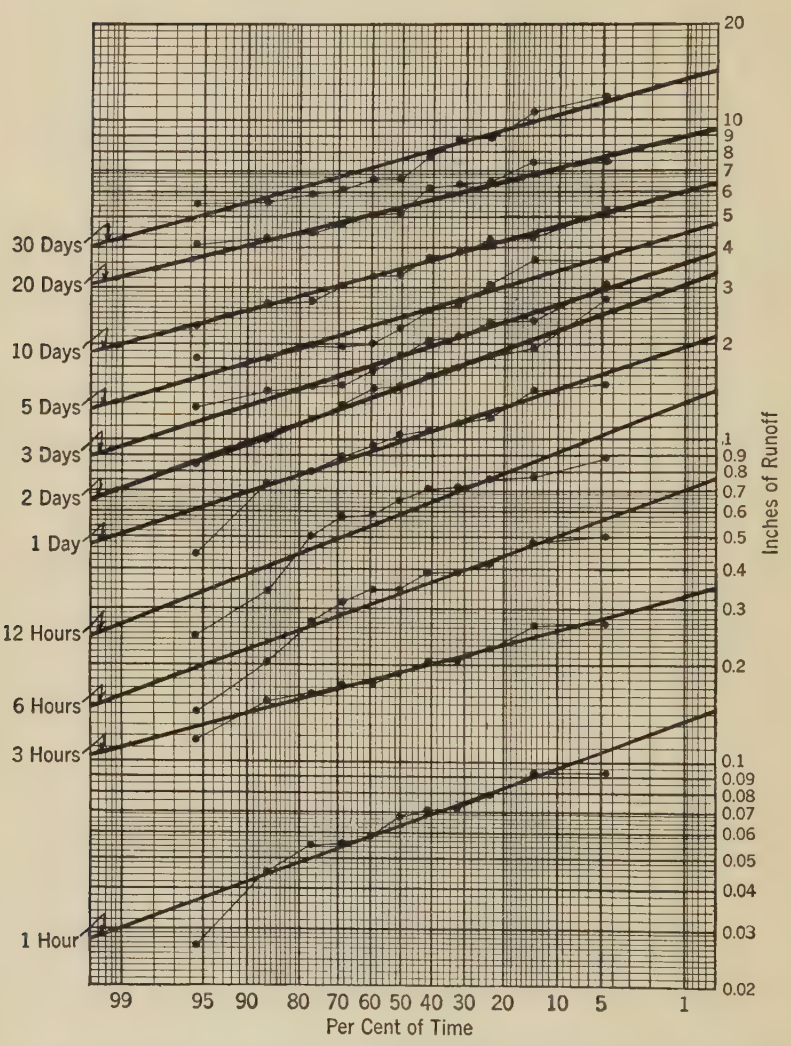

FIG. 52.—Showing the Occurrence of Floods of Varying Lengths of Time in Little River Record.

Period, days	Ten per cent chance flood, inches of runoff	Relative average rate of flow
30	10.4	0.240
20	7.1	0.246
10	4.7	0.326
5	3.4	0.473
3	2.65	0.615
2	2.22	0.770
1	1.44	1.00
Hours		
12	0.92	1.28
6	0.50	1.39
3	0.255	1.42
1	0.095	1.58

A number of interesting data of this kind were collected by Edwin S. Cullings of Watertown, N. Y., in connection with the study of flood flows of certain northern New York rivers.[2]

The following table shows the ratio of the maximum rate of discharge for each stream of the corresponding one-day flood for seven northern New York records:

Name of stream	Catchment area in square miles	Ratio of maximum rate of flow to one-day flood	
		Observed	Computed by the Fuller formula
Black River	1878	1.06	1.21
Moose River	366	1.66	1.34
Oswegatchie at Harrisville	256	1.12	1.38
Oswegatchie at Heuvelton	994	1.05	1.25
Grasse River	334	1.17	1.35
St. Regis	616	1.25	1.29
Raquette	723	1.04	1.28
Average	.....	1.19	1.30

[2] Report on Control of Floods in Northern New York Rivers, by Edwin S. Cullings and Allen Hazen.

It will be seen that in a majority of cases, and on an average, the ratio was less than computed by the Fuller formula and frequently considerably less. This may be accounted for in large measure by natural storage on the meadows along the Black River and some of the other streams which equalize the flows. On the other hand, for the Moose River, which is a mountain stream without such storage, the maximum rate exceeded the average by almost double the amount indicated by the Fuller formula.

Greater Western Values.—In dry western country where floods come seldom and are large when they do come, the peak of the flood is greater in proportion to the one-day flood than is the case with eastern streams, and the ratios to be expected are both higher and more variable. Two cases will be mentioned as throwing light upon this.

At Pueblo, Colorado, in 1921 there was a very great flood which has been mentioned in another connection in Chapter X. The one-day rate was 40,000 cfs. as reported by the Geological Survey, and the maximum rate was 100,000 cfs. In this case the ratio is 2.5 for a stream with a catchment area of 4600 square miles. The explanation seems to be that water came down a steep slope with great rapidity, perhaps almost in the form of a bore. At any rate bores have been observed where such torrents come down dry stream beds following cloudbursts in the mountains in various parts of the world.

There was another case similar to this, but in a smaller stream, at the Sweetwater Dam at San Diego, California, which was made the subject of special study.[3] The catchment area in this case is 181 square miles and the average runoff through a term of years is about 1.65 inches per annum. In sixteen days there was a runoff of 11.55 inches, which is equal to the average runoff in seven years. The one-day flood, as defined in Chapter II; namely, the greatest record for one regular twenty-four-hour period, was 15,000 cfs. The flows reported in Water Supply Paper 426 have been plotted and values taken from the curve which show the limits that were exceeded through various lengths of time, and the average rates through those times were computed with the following results:

[3] U. S. Geological Survey Water Supply Paper, 426.

FLOOD FLOWS—SWEETWATER RIVER, JANUARY, 1916

Interval between certain flow limits	Rate of flow at beginning and end of interval	Average rate of flow during interval
Maximum	45,500	
1 hr.	42,000	45,000
2 hr.	37,000	42,000
4 hr.	32,000	38,000
6 hr.	27,000	35,000
12 hr.	17,000	29,000
24 hr.	10,000	20,400

Maximum one-day flood, that is, for usual record period, 15,000 cfs.

In this case the Fuller factor is 1.42 but the actual peak of the flood was three times the one-day flood and more than double the indication of the Fuller factor. The indications are that the Fuller factors for maximum rates of flow should be limited to eastern conditions, and should not be used in the west.

In the Sweetwater flood there was an unusual difference between the one-day flood and the twenty-four-hour flood as defined in Chapter II. The greatest twenty-four-hour flood ran approximately from noon on the 27th to noon on the 28th and during this period the average rate of flow was 20,400 cfs. This flow was divided between two days' records which were parts of the other days and resulted in 15,000 cfs. being reported for January 27 and 9,970 cfs. being reported for the 28th. In this case the twenty-four-hour flood is 36 per cent greater than the one-day flood. This may be taken as an extreme case of difference.

This Sweetwater flood record was studied in considerable detail by the author with reference to spillways for other reservoirs in California. It was found that, because of the sharpness of the peak, such a moderate amount of storage as was usually available behind the freeboard of a dam with the reservoir of ordinary size would smooth it out in great measure so that the maximum amount passing the spillway would be much less than the maximum flood. Freeboard storage in some assumed cases—applying actual runoff to other reservoir conditions

—brought the required rate of spill down to an approximation of the twenty-four-hour average of 20,400 cfs.

This Water Supply Paper deals with flood conditions in other southern California streams during the same storm and deserves careful study in connection with spillways and other works in all that part of the west which is dry and in which more or less similar conditions must be anticipated.

Some time in the future when many more records are available and cover longer periods, the curves that represent the chances of such extreme floods may be reduced to usable form.

It is known that cloudbursts occur in the desert from time to time and that great floods on small areas may be produced at any point, but at very long intervals. The typography of the desert and its canyons is evidence of this.

There are many instances of floods beyond the ordinary on streams for which no records exist to establish what the average flood is. Some use of these may be made in throwing light on rare floods of great magnitude. This will be taken up further in the next chapter.

Local Character of Great Floods.—The local character of great storms is clearly shown in the report of the Miami Conservancy District to be mentioned in the following chapter. The local character of great floods is intimately connected with it.

The storm which produced the Johnstown Flood in 1889 extended over a wide strip of country and made great floods in many rivers, but the floods in different streams within the area affected were not by any means of the same relative magnitude. Some streams made records above those noted before or since, but others showed much less relative increase.

In the great Vermont flood of November, 1927, when the rainfall and runoff were at their highest peaks in many places and when there were also great floods in the western part of Massachusetts it is to be noted that at the Greenfield, Mass., water-works the flow at the intake dam did not even reach the highest flow for that year. With areas on both sides experiencing record floods, here was a spot between where the maximum rate was not even up to an annual flood.

Floods in different streams do not ordinarily run closely parallel and there may be wide differences even when the catchment areas are close together.

Floods from Broken Dams.—Man needs to control the flow of rivers and in doing this builds reservoirs and dams. Reservoirs and dams tend to reduce flood flows and serve to make available for power, irrigation, navigation, and for domestic and industrial water supply additional quantities of water above natural flows. Dams are also built sometimes to form artificial lakes to be used for ice ponds, pleasure resorts, and other purposes.

Dams sometimes break, and when they break, floods may be produced in the rivers below. Some of the most destructive floods in America have been caused by dam failures. It may be a flood that puts the last bit of pressure on the dam or that exceeds the capacity of the spillway and thus leads to the failure of the dam. Of course, it is true that if a dam were strong enough, as all dams should be, it would not be broken by any flood that could be anticipated; but, in human experience, dams that are not strong enough are sometimes built, and such dams are more likely to fail at a time of flood than at other times.

When the dam fails, the water back of it flows out rapidly and increases the flood in the stream below. In almost every great flood on the large rivers of the country some small dams on tributaries fail and the water so released is added to the flood volume. Ordinarily the amounts added in this way are not large enough to be of much practical importance in the general flood.

In other cases where the reservoirs are larger, and greater in proportion to the stream size and flood volume, the volume of flood flow may be increased very greatly above anything that would ever have happened in the natural course of events. Such floods do not follow any law that can be ascertained. Each case of this kind must be considered by itself. No attempt should be made to apply the methods used in the preceding chapters to a flood of this kind, whereas, on the other hand, floods in which water from broken dams is a considerable element should be rigorously excluded from the data to which such methods are applied.

In considering floods of this kind, it is not always the largest reservoir or dam that in breaking does the most damage. A small reservoir above a narrow valley with much human population may cause a great disaster, whereas the break of a much

larger reservoir under more favorable conditions for the discharge of the impounded water may do much less damage.

Disastrous floods and broken dams therefore do not run parallel.

The following are some of the disastrous floods in the United States, caused by dam failures:

Williamsburg, Massachusetts: 1874

Mill River Dam; earth embankment with longitudinal wall of stone; length 500–6 feet; 43 feet high; area of reservoir, 111 acres; depth, average 20 feet; 143 lives lost; damage $1,000,000.

Johnstown Flood: 1889

South Fork Dam; capacity 5,000,000,000 gallons; 72 feet high; area of reservoir, 400 acres; average depth 30 feet; 2,142 lives lost; damage $9,000,000.

Walnut Grove Dam, Hassayampa River, Arizona: 1890

Rock fill; 400 feet long; 110 feet high; 140 feet thick; area of reservoir, 1000 acres; 150 lives lost; damage $800,000.

Austin, Pennsylvania: 1911

Bayliss Dam; gravity masonry; 47 feet high; 15,780 cu. yd.; capacity of reservoir, 200,000,000 gallons; 200 lives lost.

Lower Otay Dam, California: 1916

Part of the water supply of San Diego; 130 feet high and stored a large volume of water; 30 lives lost.

St. Francis Dam, California: 1928

Part of the Los Angeles water supply system; about 200 feet high; capacity of reservoir, 12,000,000,000 gallons; more than 200 lives lost.

These are only the big failures. There are many others, in which smaller numbers of lives have been lost.

Dams are being built in great numbers and their use must increase. Most of the dams built are good, and strong enough to prevent floods of this kind. To secure future safety some of the weakest of the dams now standing should be strengthened; and all new dams should be built to conform to rigorous standards that will insure safety.

CHAPTER XV

EFFECTS OF GREAT STORMS

Great floods are produced by great storms. The study of storms is necessarily associated with the study of floods. The data in regard to rainfall are much more numerous and in many cases, no doubt, more accurate than the data in regard to flood flows.

It is natural that rainfall conditions should be studied in an effort to understand and account for flood flows and to get a notion of the probability of the recurrence of the conditions that have produced destructive floods.

The U. S. Weather Bureau has a tremendous amount of data in regard to rainfall at a large number of stations and extending over many years. In flood-flow records there is nothing approaching this volume of data even in a remote degree. If definite relations between rainfall and runoff could be established, the problem would be simplified. Competent men have put plenty of hard work upon the study of these relations, and much has been learned, but there are limits. The relations are variable because there are innumerable conditions, besides those that are taken into account, that affect the proportions and the rapidity of runoff.

One of the difficulties in the study is understanding the rainfall data. There is nothing more discouraging than a great mass of data that has not been arranged and studied with reference to the problem in hand.

Miami Conservancy District Studies.—After the Dayton flood of 1913, the Miami Conservancy District was formed to build reservoirs, to enlarge river channels and to do other work necessary to prevent recurrence of flood damage. Arthur E. Morgan, Chief engineer of the District, carried out a study of the Weather Bureau records that is unique. The results are contained in Part V of the Miami reports. The study covered

all records of the U. S. Weather Bureau east of the Rocky Mountains, and the results have been arranged so that it is possible to see what these records indicate for high rates of precipitation and so that they are of practical use when applied to actual problems.

The entire country was divided into quadrangles by lines of latitude and longitude at two-degree intervals. The data in each quadrangle were treated as a single series. These studies were carried out in parallel for one-day, two-day and longer periods up to six days.

Maps of the country were then made showing on an average the limits of rates of rainfall that would be exceeded at any one station in certain time intervals. These maps make it possible, at a glance, to see for any locality what high rates of rainfall may be anticipated in certain intervals of time. They further show some of the basic data in regard to each quadrangle, which may be taken as starting points for more intensive study of local conditions where that is desirable.

The report then proceeds with a description of some thirty-five of the most notable storms that have swept the country in the entire period covered by the Weather Bureau records. The descriptions are accompanied by maps. The records of each rainfall station were first plotted for each storm and lines were drawn to represent rainfalls of equal intensity. These maps have been reduced to a small scale for publication, omitting the individual records which were too numerous to be shown on the small-scale maps. The maps, of which there is a whole series, give a vivid picture of heavy storm conditions that cannot be otherwise obtained. The areas in which the precipitation exceeded various limits have been taken off from these maps by planimetering, and the results are presented both in tables and in diagrams. Each major storm is shown separately.

If one compares these maps and records with the great floods that have occurred in the last forty years, it will be found that many or most of those floods were occasioned by some one of the storms represented by these maps and tables.

Taking it altogether, this report is very much the best treatise on great storms that is available. It is based entirely on Weather Bureau records, but it is interesting to note that it was compiled and made available by a study outside the

Bureau. It may be taken as a type of what will be done sometime with the flow records now being accumulated by the U. S. Geological Survey.

The author, as a result of studying this monumental work of Morgan's and combining the data drawn from it with certain data from Meyer's book on hydrology [1] and data from other sources, arrived at approximate factors to apply to the base storm rate to find the probable precipitation in storms of other degrees of probability and also to find the probable rates of precipitation for various lengths of time.[2]

As a starting point we may take Morgan's figure showing isopluvial lines for a hundred-year period and one-day rainfall. This is one of a series of twenty-four charts and is here reproduced from the Miami report in Fig. 53. This chart shows the limit of twenty-four-hour precipitation that may normally be expected once in a hundred years in any locality. Putting it in the form of expression that we prefer, there is one per cent chance that the values shown by these lines will be equaled or exceeded at any rainfall station in any one year.

The lines showing the limits range from five inches for one day in the North to eleven inches in southern Louisiana and Texas. The six-inch line passes through Massachusetts, New York, Pennsylvania, Maryland, Virginia, Kentucky, Indiana, Illinois, Iowa, Wisconsin, Nebraska, Kansas, Oklahoma, and Texas, and is representative of a large and very important part of the country. Where the six-inch line passes, the rate of rainfall within certain limits may be expected about as shown in the table on page 142.

The values in this table are shown graphically in Fig. 54. To adjust the values shown by the diagram and given in the table to other conditions, consult the Morgan map, herewith reproduced as Fig. 53. Find the probable one per cent chance rainfall for the locality in question and increase or decrease all the figures for rainfall in the table in the ratio of the value found for the one per cent chance rainfall to the six inches on which the table is based.

For a more exact local estimate, local data should be collected, all data brought up to date, and the whole matter re-

[1] Elements of Hydrology (John Wiley & Sons, 1917).
[2] Engineering News-Record, Vol. 87 (1921), p. 858.

MAXIMUM AMOUNTS OF RAINFALL IN INCHES TO BE EXPECTED WITHIN VARIOUS LIMITS OF TIME, AND WITH FOUR STATED DEGREES OF PROBABILITY FOR USE WHERE THERE IS A ONE PER CENT CHANCE OF SIX INCHES OF RAINFALL IN ANY ONE DAY IN ANY ONE YEAR

Length of period	Ten per cent chance equalled or exceeded in any one year	One per cent chance equalled or exceeded in any one year	0.1 per cent chance exceeded in any one year	0.01 per cent chance exceeded in any one year
6 days	5.75	9.05	12.25	15.80
3 days	4.85	7.95	10.85	13.90
2 days	4.43	7.30	10.15	13.00
1 day	3.75	6.00	8.80	11.50
12 hr.	3.25	5.20	7.40	9.80
6 hr.	2.83	4.50	6.30	8.40
3 hr.	2.47	3.85	5.35	7.00
2 hr.	2.28	3.50	4.85	6.35
60 min.	1.93	2.90	3.91	5.00
30 min.	1.44	2.09	2.77	3.50
15 min.	1.00	1.43	1.83	2.27
10 min.	0.81	1.09	1.40	1.78
5 min.	0.50	0.70	0.91	1.18

The values in the table were prepared by combination of data of Morgan in the Dayton Report; of A. F. Meyer in his book, "Elements of Hydrology"; of Sherman in the records of Springfield, Mass.; of Holmes in the records of Syracuse, New York; and of Eddy in the records of the rain gaging at Chestnut Hill Station, of the Boston water-works.

examined on all the evidence that may be available. For that part of the United States not covered by Morgan's map, the only procedure is to examine the local data and arrange them in the way that Morgan has used, or an equivalent, and to determine from them the corresponding values.

All of the above relates to rainfall at one station. When larger areas are considered, the average rate of rainfall will be less, and the larger the area the smaller will be the average rainfall in a corresponding length of time.

Morgan has compiled in a most painstaking way the depth in inches of the greatest rates of rainfall over areas of various sizes for thirty-four of the most important storms in the eastern

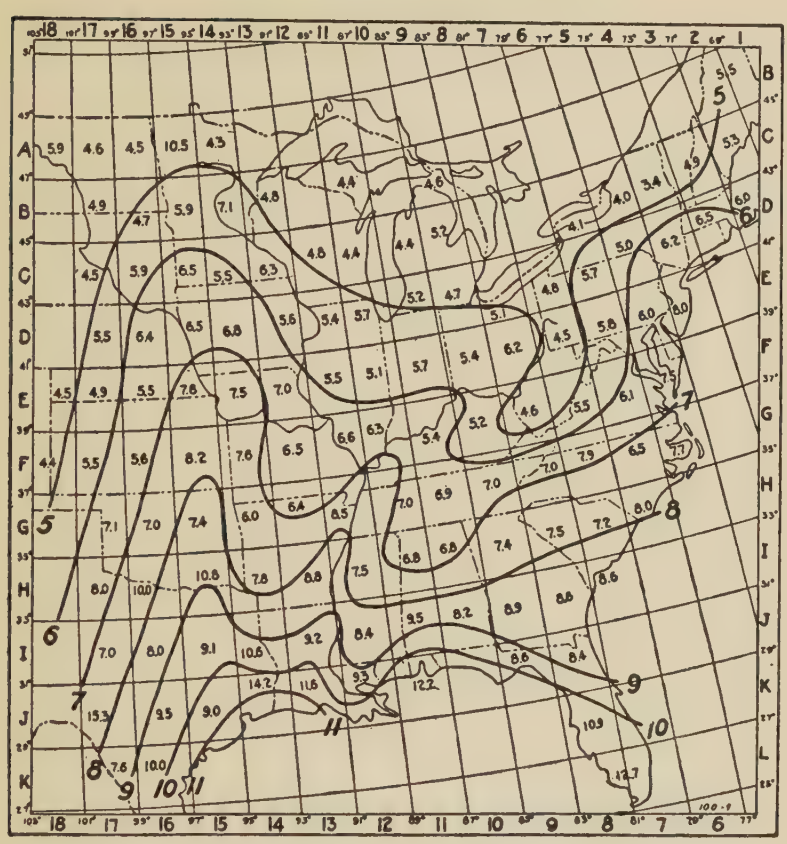

FIG. 53.—Isopluvial Chart Showing 1 Per Cent Chance, One Day Rainfall. Reproduced from Miami Conservancy District Technical Reports, Part V, p. 95, 1917.

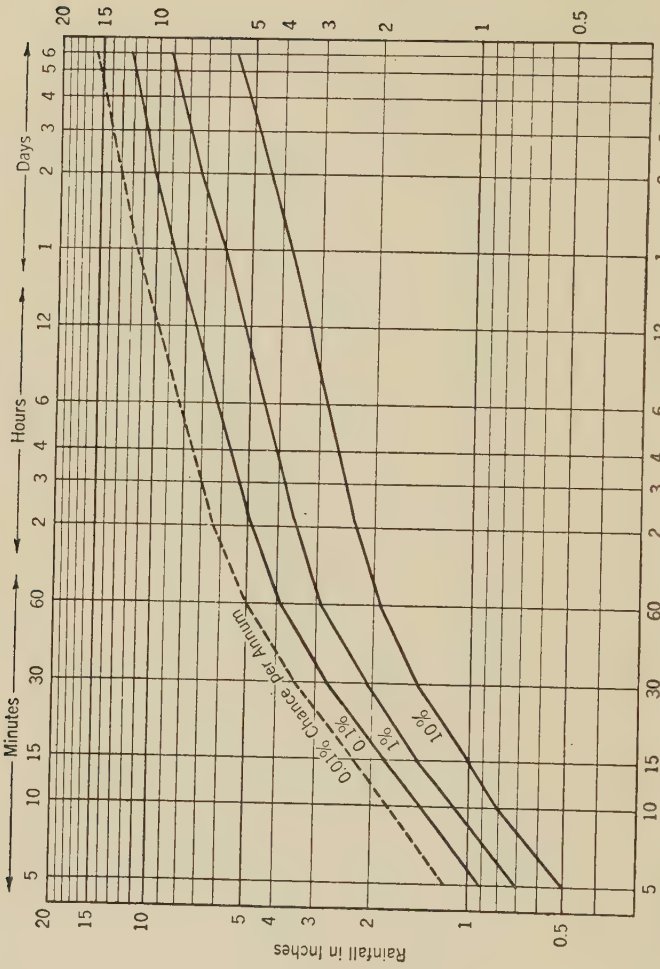

FIG. 54.—Expectancy of High Rates of Rainfall where the 1 Per Cent Chance One-day Rainfall is 6 Inches.

United States within the period covered by sufficiently complete rainfall data. Seventeen of these storms were in the north and seventeen in the south. The results for twenty-four hours he has summarized in the next table.

DEPTH IN INCHES OF THE GREATEST AVERAGE RAINFALL OVER AREAS OF VARIOUS SIZES FOR SEVENTEEN IMPORTANT STORMS IN THE NORTHERN PART OF THE UNITED STATES

Storm			Greatest 24-hr. rainfall over area in square miles					
Number	Date	Center	1	500	1000	2000	4000	6000
a	1869, Oct. 3–4	Conn.						
c	1889, May 31–June 1	Pa.	8.4	7.8	7.5	7.3	7.1	6.8
10	1894, May 18–22	Pa.	5.8	5.5	5.3	4.9	4.3	4.0
15	1895, December 17–20	Mo.	5.8	5.8	5.7	5.7	5.5	5.4
25	1897, July 12–14	Conn.	8.0	7.3	6.8	6.2	5.6	5.2
51	1900, July 14–16	Iowa	7.0	6.8	6.6	6.3	5.8	5.4
72	1903, August 25–28	Iowa	11.2	10.6	10.0	9.1	7.8	6.8
76	1903, October 8–9	N. J.	11.5	9.3	8.4	7.6	6.8	6.3
83	1905, June 9–10	Iowa	12.1	10.9	10.0	8.9	7.8	6.9
86	1905, Sept. 15–19	Mo.	8.1	7.4	6.9	6.2	5.5	5.0
109	1909, July 5–7	Mo.	9.7	8.0	7.2	6.1	5.0	4.3
110	1909, July 20–22	Wis.	10.7	9.0	7.9	6.5	4.9	
114	1910, October 4–6	Ill.	8.5	7.5	7.1	6.5	5.9	5.6
125	1912, July 20–24	Wis.						
130	1913, Jan. 10–12	Ark.	5.8	5.6	5.4	5.1	4.9	4.7
132	1913, March 23–27	Ohio	7.0	6.7	6.5	6.2	5.8	5.7
151	1915, August 17–20	Ark.	7.0	6.6	6.5	6.5	6.4	6.2
	Average	.....	8.43	7.65	7.18	6.60	5.94	5.60

DEPTH IN INCHES OF THE GREATEST AVERAGE RAINFALL OVER AREAS OF VARIOUS SIZES FOR SEVENEEN IMPORTANT STORMS IN THE SOUTHERN PART OF THE UNITED STATES

Storm			Greatest 24-hr. rainfall over area in square miles					
Number	Date	Center	1	500	1000	2000	4000	6000
b	1887, July 27–31	Ga.	10.0	8.9	8.3	7.5	6.6	5.9
13	1894, Sept. 24–26	Fla.	12.5	10.8	10.3	9.6	8.6	8.0
24	1897, March 22–23	Ga.	10.3	9.6	8.9	8.1	7.1	6.3
43	1899, June 27–July 1	Texas	11.0	9.9	9.4	8.8	8.0	7.4
49	1900, April 15–17	Miss.	12.7	10.3	9.9	9.4	8.6	7.9
63	1902, March 26–29	Miss.	9.0	8.7	8.3	7.8	7.3	7.0
93	1906, Nov. 17–21	Ark.	8.0	7.5	7.3	7.0	6.6	6.3
102	1908, July 28–Aug. 1	La.	9.6	8.8	8.2	7.0	5.7	4.9
103	1908, Aug. 24–26	N. C.	11.7	9.2	8.2	6.8	6.3	6.0
105	1908, Oct. 20–24	Okla.	6.3	6.2	6.0	5.8	5.5	5.3
108	1909, June 29–July 3	Fla.	12.0	11.5	10.3	8.8	7.6	6.8
135	1913, Oct. 1–2	Texas	13.0	12.3	11.7	10.7	9.2	8.3
136	1913, Dec. 2–5	Texas	10.0	8.5	7.5	6.6	6.3	6.0
144	1914, Oct. 14–15	N. C.	10.0	7.3	6.3	5.8	5.2	4.6
151	1915, August 17–20	Texas	9.1	8.7	8.0	7.9	7.7	7.5
156	1916, July 6–10	Ala.	11.1	10.7	10.2	9.5	8.8	8.2
157	1916, July 14–16	N. C.	19.3	12.2	11.3	9.9	8.4	7.5
	Average	.....	10.90	9.49	8.82	8.06	7.27	6.69

The average results for all these storms may be combined in a single short table from which it appears that taking the maximum twenty-four-hour precipitation at one rainfall station as 100, then the corresponding average rate to be expected on certain areas will be as follows:

Area, square miles	Maximum average rate
1	100
500	89
1000	83
2000	76
4000	68
6000	64

Morgan's tables show precipitations for longer periods up to six days, but it is unnecessary to go into these details at this time. It may be stated, however, that as the time interval used as a basis of comparison increases, the difference in rate for areas of different sizes become less.

Reasoning from the Results.—In considering these results, it is to be borne in mind that these rates of precipitation were those that applied to that selected area on which precipitation was highest in any one storm and such rates probably would not apply to an equal area selected in advance.

A catchment area of a river is fixed in position and takes what comes to it, and the square miles representing its area cannot be moved to fit the center of the storm. Therefore it seems likely that the chance of the occurrence of a precipitation as great as the limit shown in the above table on any one particular catchment will be reduced. In other words, the chances are that the particular 4,000 square miles of maximum rainfall, or whatever the area may be, will not coincide with the catchment area of any given stream, but will overlap parts of several such areas and contribute to smaller floods on a number of them.

Taking the above stated figures for rates of precipitation, on areas of different sizes, it is found that the increase in total water falling upon areas ranging from 500 to 6,000 square miles increases as the 0.87 power of the area. This may be compared with the 0.80 power used in Chapter V to represent the rate at which runoff quantities increase with area.

Rainfall is the source of runoff, but many other factors come into play, among them the retardation and greater dispersion through intervals of time of flood flows from a larger area. On a small area the flood water from all parts of it arrive at a given point within a relatively short period of time, but from a larger area the flood waters from parts of the area will have mainly passed before flood waters from other parts begin to arrive. This is sometimes referred to as the concentration of flow.

It is noted both from the map showing the limits of one hundred-year rainfall (Fig. 53) and from the table of storms for the north and south, that the precipitation is considerably greater in the south than it is in the north. In a similar way the records of annual floods in the Atlantic Coast Region,

divided into two parts, show slightly greater flood volumes in the south.

The difference in average flood volumes is by no means as great as the difference in average rainfall. No doubt the higher rainfall in the south is offset in considerable measure by greater evaporation at higher temperatures. It may be also that with higher temperatures the average condition of the soil at the beginning of a storm is drier and has more absorbing power. The snow factor in the south is less.

Taking it altogether, the storm and flood conditions north and south along the Atlantic Coast and in the first states west of the Allegheny Mountains are surprisingly uniform.

Relations between rainfall and runoff differ with climate. In very wet climates they seem to be simpler and more clearly defined. There are cases where the rainfall is heavy, the evaporation relatively small, and the runoff is a much larger percentage of the rainfall than it is in the eastern United States. Then rainfall is a better guide to runoff estimates. On the other hand, in the arid interior there will be places where runoff is mainly limited to the flows that immediately follow the heavier storms and the amount is a small and most variable percentage of rainfall.

For our present purpose, only a very general picture of rainfall conditions is attempted. For more details the Miami report should be studied, remembering always that river gagings rather than rainfall data will furnish the best basis for estimates of flood flow. Such a view of rainfall conditions will form an appropriate and necessary background and will help in understanding the runoff records and in drawing sound conclusions from them.

CHAPTER XVI

EFFECTS OF STORAGE, FORESTS, AND LAND DRAINAGE

Storage.—Lakes and reservoirs sometimes play an important part in modifying and reducing flood flows in the streams that flow from them. The total flow is not reduced but it is spread over a longer period.

Some reservoirs, like those of the Miami Conservancy District, have been built for the express purpose of storing flood flows and protecting the channel below. They are normally empty and their capacity is always available for holding back flood flows.

Other reservoirs have been built to conserve water for navigation, irrigation, power, or public water supply. Such reservoirs will also hold back flood flows but in varying degrees. If the water in the reservoir is low when the flood flows start, the space will be filled before there is overflow. There will be reduction in flood flows that will be more or less complete according to the relative volumes. If the reservoir is full when the flood flow starts, there is still some freeboard storage that will come into play. It may be great or small according to circumstances, but the tendency is always to reduce flood flows.

If the storage is very large, so as to give complete utilization of the water of the stream, most floods will be completely absorbed in storage and the valley below will be protected from them.

As a case in point may be mentioned the Elephant Butte Dam on the Rio Grande which apparently has never had water over its spillway in the twenty years of its service. An example on a smaller scale is furnished by the reservoir on the Singleterry stream in central Massachusetts, regarding which it was testified in a court proceeding that in the memory of man the reservoir had never been either empty or full. Water had been

drawn as needed for power and as available, and not otherwise. That is a one hundred per cent development and one that completely eliminates the flood tendencies of the controlled area so far as the lower valley is concerned.

In these cases there is always the possibility that a very large flood might come at a time when the reservoir would be full or nearly full, and that the reservoir would overflow, and would produce a flood in the valley approximating the natural flow. It will not do to omit proper provision for caring for such a flood.

Many dams and reservoirs, especially in the last few years, have been provided with siphon spillways, Taintor gates or Stoney gates—sometimes of great size, with a view to holding a constant water level during flood periods. So far as this purpose is accomplished, the value of the reservoir for reducing flood flows is eliminated. If such gates could be brought to a state of perfection and be depended on to hold the water level unchanged through a great flood, then the reservoir would have no influence on flood quantities in the stream below. This, however, is a condition hardly to be expected. Ordinarily the use of such gates diminishes the flood reducing value but does not entirely remove it.

Lakes and reservoirs are not the only facilities for storage useful in reducing flood flows. The meadows along many streams are overflowed at flood stages and this storage capacity tends to reduce the maximum flood flows in the valley below by extending the period of discharge over a longer interval.

In other cases there is an important amount of storage in the soil, especially where the soil is sandy or gravelly and well drained. The soil must be drained to make such storage effective, because sand flats that are water-logged have no reserve storage capacity. Underground storage in them has no value in reducing floods.

There are streams in sand-hill countries where the storage is so great as to completely equalize all the ordinary variations in flow and to afford almost complete protection against such floods as would exist with similar topography and impervious soil. In these cases the protection is more complete against moderate floods than against extreme floods. The storage capacity of the ground that equalizes a moderate flood may be over-

taxed by the larger storm, and after the underground reservoir is filled up all the surplus water must flow away.

When storage is used to reduce flood flows, the reduction is not quite in proportion to the area controlled even when the control of that area is complete.

Sometimes it is possible to put a storage or detention reservoir on the stream shortly above the point where it is to be controlled, as was done for instance in the flood control dam built a few years ago at San Antonio, Texas, but in most cases the valley of the main stream is occupied by railroads, industries, and other uses to such an extent that a flood control reservoir in it is practically impossible. Flood control by reservoirs some distance up a stream or on tributaries will be more frequently practicable.

All storage, whether built primarily for flood control, for development of power, or for any other purpose, will tend to reduce flood conditions; but the amount of reduction to be actually obtained may be less than one would naturally expect from a consideration of the areas.

The accompanying calculation is made for a stream with an area of 1,000 square miles with a flood coefficient of 80 and for a one per cent chance factor of 2.29.

In tabular statement are shown the floods with successive

Effect of Storage on Flood Control on a Catchment of 1000 Square Miles.

Area controlled by storage	Effective area being area not controlled plus ten per cent of controlled area	One per cent chance one-day flood—cfs.	One per cent chance maximum flood—cfs.	Percentage controlled by storage	Percentage reduction, one-day flood	Percentage reduction, maximum flood
0	1000	46,000	57,700	0	0	0
100	910	43,000	54,000	10	6	6
200	820	39,500	50,000	20	14	13
300	730	36,000	46,000	30	22	20
400	640	32,300	41,800	40	30	28
500	550	28,700	37,200	50	38	36
600	460	24,900	32,900	60	46	43
700	370	20.900	28,000	70	55	52
800	280	16,800	23,000	80	64	60
900	190	12,300	17,200	90	73	70

storage and control of areas in blocks of 100 square miles. This is made on the assumption that the controlled area is brought under 90 per cent control and that the water escaping from such area, in time of extreme stress, will amount to ten per cent of the natural flow of those areas.

The percentage of reductions in flood quantities by the control of similar percentages of other areas would be the same for the one-day floods, but the proportions would vary somewhat for the maximum floods according to the size of the areas.

Without following the matter further it is apparent that approximately two-thirds of the entire catchment area must be fully controlled by reservoirs to effect a reduction of 50 per cent in the flood quantities. Similar ratios will be found for other proportions.

Forests.—The extent of the influence of forests upon low water flows and flood quantities has been debated for years. The foresters have urged the importance of forests in controlling and regulating stream flow, increasing the quantities of water available for use, and preventing or reducing flood flows. The public has very generally accepted this point of view.

The water-works engineers of the country have required some proof before they could accept this popular doctrine. There has been much argument, but it must be considered that real evidence of the effect of forests upon stream flow is meager and unsatisfactory. The matter is a hard one to prove one way or the other in a conclusive way.

General H. M. Chittenden discussed this matter in 1908,[1] and twenty years afterward his statement can hardly be improved upon.

He states that the commonly accepted opinion is that forests have a beneficial influence on stream flow:

(1) By storing the waters from rain and melting snow in the bed of humus that develops under forest cover, preventing their rapid rush to the streams and paying them out gradually afterward, thus acting as true reservoirs in equalizing the runoff.

(2) By retarding the snow-melting in the spring and prolonging the runoff from that source.

(3) By increasing precipitation.

(4) By preventing erosion of the soil on steep slopes and thereby pro-

[1] Transactions Am. Soc. C. E., Vol. 62 (1909), p. 245.

tecting watercourses, canals, reservoirs and similar works from accumulations of silt.

There are many subsidiary influences, but, broadly stated, the above propositions cover the ground.

General Chittenden's study had a negative conclusion. He found that no material influence upon stream flows could be attributed to forests.

The long discussion of General Chittenden's paper participated in by foresters and hydraulic engineers presents the matter from many standpoints. It occupies three hundred closely printed pages in the Society's Transactions, and is the most comprehensive and best discussion of the subject available after all these years.

Eight years later General Chittenden, in discussing another paper on Floods and Flood Protection, wrote:[2]

It may be questioned, however, whether today there is much controversy among well-informed engineers as to the essential principles involved. Is not the consensus of professional opinion that, in times of excessive rainfall, in which really great floods always originate, the restraining effect of forest cover, whatever it may be in ordinary storms, becomes exhausted and is of no effect? This is the official opinion in France, even in forestry circles, as is shown by the following extract from a report by the Director of the French Forestry Service on the 1910 flood of the Seine:

> In the exceptional circumstances which always produce the floods of the Seine, the action of forests, whether evergreen or deciduous, becomes for the moment negligible in its effect on the volume of water carried by the river.

Engineers are apparently agreed on this essential point. In formulating plans for flood control, they would not dare to reduce in any degree the effectiveness of direct measures, such as reservoirs, levees, etc., by any possible measures of reforestration.

Undoubtedly forests affect stream flow in many ways but there is no evidence that they materially modify major flood flows. There is no reason to think that clearing of land in our country and putting it under cultivation has materially increased the flood quantities over those that existed in previous centuries. Reforesting cleared and burned mountain areas at the head waters of rivers is advantageous from many aspects, but is not to

[2] Transactions Am. Soc. C. E., Vol. 81 (1917), p. 1256.

be counted on to make a material reduction in floods in the rivers flowing from them.

There was further discussion of the problem of forests at the Columbus meeting of the American Society of Civil Engineers, in October, 1927.[1]

Drainage.—It is sometimes thought that land drainage facilitates the rapid runoff of rainfall and therefore increases flood quantities on the rivers where agricultural drainage has been extensively carried out. Evidence in regard to this question was carefully collected by Profs. S. H. Woodward and Floyd A. Nagler of the University of Iowa in a most painstaking way and presented at the Columbus Meeting of the American Society of Civil Engineers in October, 1927.[2]

The evidence so presented is negative. Apparently other conditions introduced by drainage offset the increased rate of flow directly due to drainage so that the total result of agricultural drainage is not important in maximum flood quantities.

One of the effects of drainage is to create ground storage where none existed before. Wet and marshy soil in swamp areas has no ground storage. There will be temporary storage over the surface of such wet areas in times of heavy rainfall, but where the ground itself is normally water-logged it is without value as a reservoir for holding back flood flows.

The most effective and instantaneous of all reservoirs, so far as flood control is concerned, is the surface soil; and this is available only to the extent that at the beginning of a flood period it is drained and its pores are filled with air which may be replaced with water. Drainage takes the water out of swamp soil and creates a storage space where none had existed. The effect of soil storage is greatest in taking care of runoff from summer or early autumn storms after the soil has been thoroughly dried out, but it may be much less with respect to late winter and early spring flood flows.

[1] Transactions Am. Soc. C. E., Vol. 93 (1929), pp. 716 and 840.
[2] Transactions Am. Soc. C. E., Vol. 93 (1929), p. 821.

CHAPTER XVII

OBSTRUCTIONS, DEBRIS AND SEDIMENT

We think of floods as being caused by great quantities of water, but with the water comes debris and sediment which accumulate in places and obstruct the channel. These with obstructions more directly traceable to the works of man frequently result in destructive water levels.

To quote again General Chittenden:[1]

If the clearing and drainage of the soil—in general terms, cultivation—do not materially affect the development and intensity of great floods, is there any respect in which man's work does enhance their destructiveness? This question admits of a definite answer in the affirmative. By obstructing nature's overflow channels man draws on himself the chief calamities which floods produce. The bottom lands along streams are just as much a part of nature's highway for carrying runoff to the sea as the normal channels between banks. They do not come into play so continuously, but they are a part of the natural waterways, and were formerly so used whenever the discharge rose above a certain volume. Man has pre-empted these channels entirely. They contain the most fertile lands, they are easiest to build on, and most convenient for roads and railroads. It is here that population multiplies and wealth accumulates, and whenever nature asserts her old prerogative of passing her floods down over them, trouble ensues. By cutting off these bottoms, greater work is forced on the ordinary channel, the flood heights are raised, and if once the waters break their bounds, they not only find wealth and people in their way, but are actually far more destructive than in their natural state. Thus man is, to a large extent, the author of his own misfortunes in the matter of flood destructiveness. The point here emphasized, however, is that man's interference with natural conditions, which so often leads to disaster, relates to his trespass on overflow channels rather than, as is popularly assumed, on the normal channels of the streams themselves. Contrary to general opinion, man's operations have, on the whole, improved the natural carrying capacity of streams. There are exceptions, of course, but the rule seems to be as just stated. A striking example is furnished by the recent studies of the Great Miami River, in Ohio. In the four prin-

[1] Transactions Am. Soc. C. E., Vol. 81 (1917), p. 1260.

cipal towns, where channel changes have been most important, the discharge capacity was found to be from two to eight times as great as in the country above and below, where man's interference has been slight. Such a condition, of course, cannot be accidental.

General Chittenden's statement cannot be improved upon.

Large floods come at long intervals. In the years between, memories are short, old residents die, newcomers do not know conditions, low lands along the river are tempting, levees are built, fills are made, warehouses, factories and all sorts of developments come in, roads are built across valleys on solid fills, with channel bridges having too small openings and, especially in the latter years, built so solidly that in case of a great flood they may serve to act as the foundation for a debris dam in front of them.

Channel Control.—There are happily some credits to go along with the debits. Dayton, Columbus, San Antonio, and many other cities have straightened and improved the channels of rivers flowing through them and have increased the discharging capacities. In other cases less radical improvements have offset more or less completely the obstructions that have been placed elsewhere within the channels. In some cases the sand and gravel industry, using materials taken from the beds of rivers, has materially increased the channel and has tended to reduce flood heights.

These credits may be small in the aggregate in comparison with the obstructions, but it is pleasant to be able to record even so much improvement. It may be expected that, as the subject is better understood, more streams will be improved in respect to flood discharging capacity.

What is needed more than anything else is to keep the channels of our rivers open.

There are millions of miles of river and stream channels. Most of the mileage is in country as yet sparsely settled and not much changed by human control. The points requiring attention are for the most part in and near cities or large towns and where there are concentrations of valuable property.

There is talk of dam supervision and control by state authorities and this has been attempted and carried out in several states.

Channel supervision would be more difficult but is often

needed because the damages to the public from floods that have come about through obstructing channels are probably much greater than those that have resulted from broken dams. It would seem logical therefore to have state control of all flood channels. This, however, would be very difficult. Carrying it out would affect the title to much riparian property and the right of the owner to use it as he sees fit. It would involve matters of judgment as to the appropriate extent of property to be reserved and judgment of different engineers would frequently vary. The subject is not well enough understood as yet and the country is not ready for any general scheme of administration of flood channels.

Competent city engineers and other public officers, however, can do much in particular cases. Railroad engineers and others working with roads and bridges can use their influence towards leaving adequate flood channels.

For some decades to come channel control will probably be a matter of individual effort rather than compulsion by force of law. A better understanding of the conditions that are involved will aid greatly. It will help those who wish to make proper reservations for flood channels, and it will help if the public understands enough of the reasons to back up competent officers in making the necessary reservations.

If some skillful dictator could mark out the lines of flood channels and hold everybody back of them it would be a wonderful thing for the country. The damages in loss of value of property along streams, thought to be very great, in reality would turn out to be less than at first believed and would be unimportant in comparison with the freedom from future damage.

The reclaimed areas along the streams could be used for park purposes in urban areas and in the country for golf courses, for cultivation and for many purposes where flooding at long intervals would not be a disaster. The important thing is to keep obstructions out of the flood channels.

It may not be amiss to point out that building levees along the Mississippi River, securing partial protection from floods to certain areas, has, on the best evidence, more than doubled the height of floods as compared with natural conditions, and it is to be reasonably expected that when the levees are made stronger

and more permanent, the flood heights will be still further increased.

Dams Across Rivers.—There are innumerable dams built across rivers for the purpose of producing water power. These dams may be distinguished in a broad way from dams built to form impounding reservoirs, but the line of distinction is not clear-cut and one class grades into the other. The main purpose of these river dams is to raise the water level and to give more head on water wheels.

Such dams increase the water level in the rivers above them for a certain distance. The increase in water level at low water stages is easily and accurately ascertained. In flood stages the water is raised for a greater distance upstream, and the effect of the dam may extend to points so far upstream as to be considerably higher in elevation than the top of the dam. Theoretically the effect extends clear back to the head waters but as a practical matter it runs out in some limited distance.

Calculations and estimates of the effect of dams on upstream conditions involve the well-known back-water-curve problem, a discussion of which goes beyond the scope of the present work.

In the Vermont flood of 1927 it is interesting to note that, in several of the villages where the damage was greatest, a dam for developing water power had been built on the stream below or near the village within a period of years so short that it had not been previously tested by a great flood. How far these dams entered into the production of disastrous results is not known with any degree of definiteness at the present time. It suffices to mention the matter here and to point out that the construction of dams to develop water power on rivers does put a certain additional flood hazard on properties within a certain range, horizontal and vertical, upstream from the dam.

In building dams of this description it is important and necessary that the back-water-curve should be studied with reference to quantities of water so great that they are to be expected only in very rare floods, and that proper provision should be made for acquiring or protecting all property that may be affected by such floods.

Floating Débris.—Rivers and streams do not ordinarily carry large floating masses but when a great flood sweeps down, cutting new channels, undermining buildings, and carrying off

bridges, floating material of all sorts is carried downstream. This may include trees, houses, wooden bridges and everything within reach of the current that will float. Even water-logged material that will not float may be dragging on the bottom.

Material of this description has to be dealt with in a great flood and frequently changes the situation completely. Temporary dams are formed where this material comes against bridge abutments or arches or against other obstructions. Even if the dam is not complete, it arrests the motion of this material in a swift current, checks and backs up the water. Water levels may rise above calculated levels for unobstructed channels.

On the other hand, however, the water quantities in a flood may be grossly overestimated because it is assumed that the water levels were those that correspond to flow in unobstructed channels.

The wooden bridges such as were formerly built and still exist on some of our streams are among the most troublesome objects of this kind. The wooden timbers in such bridges are large in size, and are often pinned together in a very secure way. When a bridge of this kind is raised off its abutments by a flood and carried downstream, it acts as a battering ram that can hardly be resisted by other bridges of either wood or iron. The only thing that will save the lower bridge is being high enough to let the floating material pass under it.

Some years ago a concrete arch bridge resting on piles and a gravelly bottom was proposed across a small river that comes out of the mountains and has large floods. The matter was referred to one of the older engineers who advised the building of a cheaper steel bridge that would go out if there were occasion for it rather than the building of a masonry structure so solid that it would hold the floating débris and form a dam because, as he said, in that event the river would probably change its course and go round the bridge instead of under it and destroy a large part of the town.

Concrete arch bridges have much to recommend them and they are bound to be built in increasing numbers, but it is important to build them high enough and with long clear spans so that they will not be likely to form temporary flood dams.

Sediment.—Streams always carry more or less matter in suspension. The more rapid the flow is, the larger the particles

that can be carried. Large slow-moving rivers in a flat country can carry little but clay. Swifter streams carry sand and gravel; and mountain torrents move the largest boulders.

Erosion is greatly increased in flood periods and vast volumes of material are sometimes moved by floods. Frequently the moved material is carried but a short distance and deposited again where conditions for carrying it are less favorable.

In the Vermont flood of 1927, two rivers changed their courses. In each case there was a pre-glacial valley in rock in which the river had no doubt flowed at some previous time. In each case this old channel had been filled up with gravel and glacial deposit and the river in modern times had flowed in a secondary rock channel higher up, at one side and some distance away from the pre-glacial one. In each case there was a dam site in this modern channel. It had been used, and water power had been developed. How large a part these dams played in moving the river back to its own pre-glacial channel it is now hard to say. In any event, during the flood, the water got out of bounds, perhaps overtopped, perhaps softened the material in the pre-glacial channel, and finally cut through, carrying in each case enormous masses of sand and gravel as well as some of the houses in the village adjacent to the river.

In these two cases in the Vermont flood, the new channel had a slope from above the dam to the valley below greatly in excess of the normal slope of the river, and it was the velocity that the water acquired in going down this steep slope that gave it its enormous cutting and carrying power. As soon as this velocity was lowered in the valley below, the eroded material, or the heaviest part of it, was deposited, and is mainly found in the old valley of the stream a short distance below the point from which it was taken up by the water.

Cones.—Mountain torrents leaving the mountains and coming out onto the plains build cones. A cone in this sense is a pile of gravel with its apex at the point in the valley where the stream issues from its mountainous channel. The slope of the surface of the cone, in all directions, except where it intersects the hills, is usually more or less constant and depends upon the conditions of flow and the suspended matter in the larger floods passing it. Such a stream thrashes around on the outer surface of the cone in due course going entirely around it, filling up the

low points with sediment and tending to hold the slope and shape, thus justifying the name of cone.

Where the exit of a mountain torrent onto the plain is more gradual through foot-hills and country of intervening degrees of roughness, the cone is distributed and is less regular but it none the less exists.

A tributary stream with high velocity builds something very like a cone on one side of a large river where it enters and tends to force the current of that river over to the opposite side.

The Missouri River entering the Mississippi at St. Louis carries an enormous load of suspended matter that the Mississippi with its lower slope and lower velocity is incapable of carrying for any great distance. This material must be deposited on the flat lands that are overflowed in flood times by the Mississippi River in its course below the mouth of the Missouri.

Variations of the same thing take place with other tributaries according to the amount and coarseness of the silts which they carry.

Providing for flood quantities of water in any such case is not enough. The sediment must also be provided for. The sediment is sure to come in quantities that vary from year to year and that vary even more greatly than the quantities of water. Any arrangement of flood channels that does not adequately provide for the retention and placing of all the sediment that cannot be permanently carried by the lower stream is bound to fail.

When floods are controlled by constructing reservoirs upon the streams, the sediment from the water passing the reservoir is mainly deposited in the reservoir. With turbid streams carrying large amounts of sediment this means that the reservoir will fill up. The period required for the reservoir to fill may be a long term of years with reference to the bonds issued to pay for the reservoir but it may be short in the life of the country.

In building reservoirs on such streams at the present time it may be well to give a little thought as to what the conditions will be after the reservoir is so filled with sediment as to reduce and ultimately to destroy its storage capacity.

The most obvious solution would be to raise the dam when that time came. In some cases there would be limits to the

amount of raising that could be done. Certainly if a dam is built with reference only to present or early conditions and not with a view to being raised, it may not be easy or perhaps safe to add to its height at some future time.

These are some of the incidental problems that grow out of great floods. They are merely mentioned here as among the things that must be considered.

CHAPTER XVIII

CHANGES IN CLIMATE

One thinks of climate and climatic conditions as more or less fixed for a given place. Past records and experience are the best guides to the future. On the other hand, we frequently hear expressions of opinion that climate is changing: the winters are not as cold as they used to be; the floods are greater than they used to be, etc.

Statements of opinion of this kind based on personal observation and recollection have little weight. Data at our disposal cover a very short period in the history of the world, but it is interesting to see what the longest records will show as to tendencies in climate.

In Fig. 55 are plotted on a small scale in thousands of cubic feet per second, the annual floods on five rivers:

Columbia, at The Dalles
Tennessee, at Chattanooga
Hudson, at Mechanicville
Connecticut, at Hartford
Merrimack, at Lawrence

No Cycles.—These curves were drawn up to see if anything like cycles in flood flows could be observed and also to see how far the annual floods fluctuated in the same way in the same years on different rivers.

Nothing that can be identified as cycles is observable in these records although there are periods when floods are more abundant than at other times.

From 1879 to 1894, there was a 15-year period when there were no very considerable floods on either the Connecticut or Merrimack Rivers. Before that period there were higher floods in general on the Merrimack than there have been in the time since this period, but the difference is not great. Increased

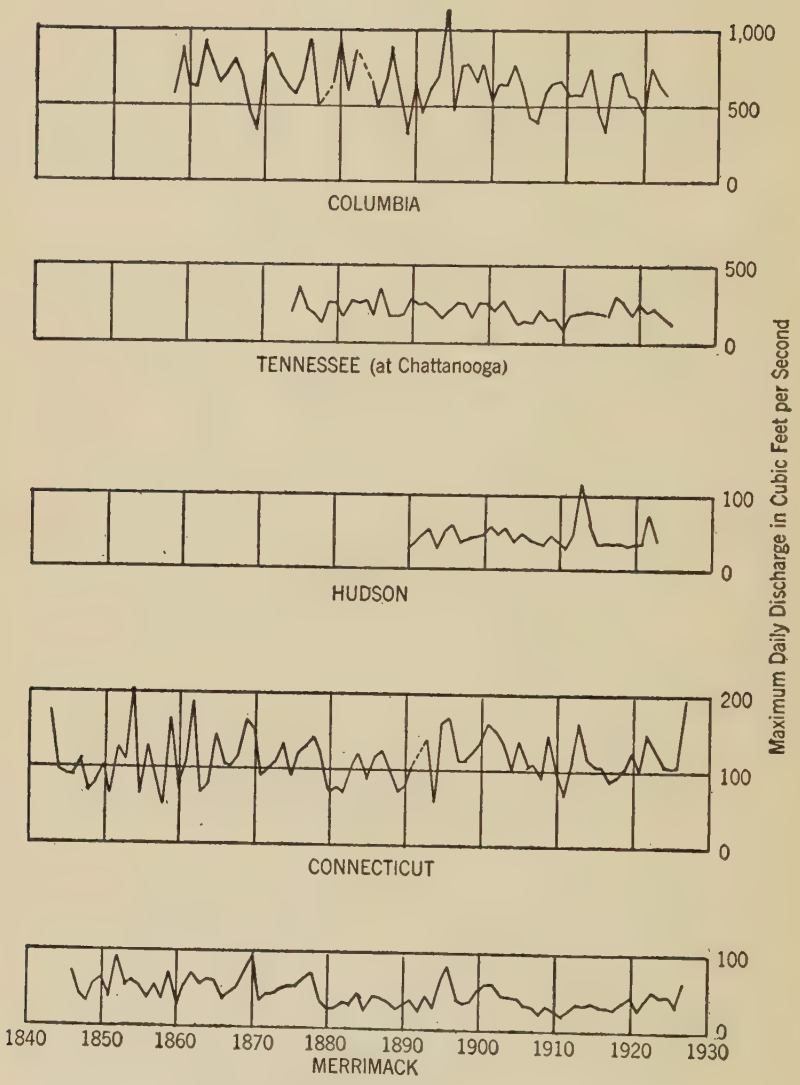

FIG. 55.—Plotting of Annual Floods in Several Rivers.

storage and diversion of certain areas for the Boston water supply have changed conditions on the Merrimack but probably not enough to be appreciable on the scale used for this diagram.

For the Connecticut at Hartford, the floods of the last twenty-five years seem to have been as great as those in the earlier period before 1878. The flood of 1927, which was greater than any before in seventy years, only slightly exceeded that of 1862 and did not reach that of 1854, according to this record.

This Connecticut River record is made by using the gage heights at Hartford with a curve of discharge made by General Ellis in 1875 and its use is based upon the supposition that there have been no material changes in the aggregate hydraulic properties of the river from Hartford to the sea in an interval of more than eighty years.

It is interesting to note that the great flood of 1913 on the Hudson was accompanied by moderately high floods in the Susquehanna and Connecticut, but that the Merrimack had no unusual flood at this time.

All this, however, is negative. There is not enough to indicate any probable change in climate. There is some indication of periods or cycles in the two longest records. We know from many other data that such moderate changes within limits are observed in temperatures, precipitation and total annual flows.

These changes are often spoken of as cycles. In particular cases a showing for cycles may be found. But the term "cycle" implies repeated returns at definite periods, and this is something that can be traced only with much difficulty and with inconclusive results in climatic matters. In a given record a cycle of 11 years corresponding to sun spots or a 34-year "Bruckner" cycle is followed for a time and then the record line goes off and the cycle cannot be further traced.

Climatic Pulsations.—Ellsworth Huntington's expression, "pulse", seems a better term to represent these changes. There are innumerable pulses in climate. There are little pulses at short intervals and big pulses at long intervals.

In geologic time there was the glacial epoch, one of the recent geologic happenings so closely behind us that many of the things that have happened since may be ascertained with considerable definiteness. From glacial times to the present there have cer-

tainly been great changes in climate. We have no knowledge of flood flows in glacial times and in times of melting ice that followed, but it may be taken for granted that they were widely different from flood-flow conditions in historic times.

Huntington has shown that in historic times during the last three thousand years there have been many changes in climate. He has carefully assembled in his book "The Climatic Factor"[1] many interesting facts concerning these changes. He has based his conclusions partly upon historic events and other information relating to regions long populated by civilized people and partly by counting and measuring the thickness of rings of annual growth of trees on mountains in relatively arid regions. He has also collected many interesting pieces of confirmatory evidence.

Historical evidence, relating to the limited parts then inhabited by people leaving records, suggests a dry period, about 1400 to 1200 B.C. At the time of Herodotus, between 400 and 500 B.C., the civilized world in northern Africa and Western Asia was moist. About 200 B.C. a drier climate prevailed, and then at the time of Christ conditions became favorable; that is, there was more moisture. For six centuries afterward the country gradually became more arid and this culminated in a very dry period about A.D. 650. Then conditions improved until about A.D. 1000, and then it was drier again until the 13th century when there was a wet spell. Since the 14th century there have been minor fluctuations. Huntington has reduced all this to the form of a curve, reproduced herewith in Fig. 56, showing both the evidence as to Asiatic climate and the rapidity of growth of old trees in California and Arizona.

Huntington concludes that during historic times there have been incessant climatic pulsations that seem to be of essentially the same nature as the greater ones that occurred during the glacial and post-glacial epochs. He concludes that the conditions of the geologic past merge without break into those of history and the present time.

It is not to be supposed that these changes have been simultaneous over the whole world. One country has been dry while another had conditions more favorable to human life and civilization. The changes have followed in such a way that first one

[1] Publication 192, Carnegie Institute of Washington, 1914. See also Civilization and Climate, by the same author, Yale University Press, 3rd edition, 1924.

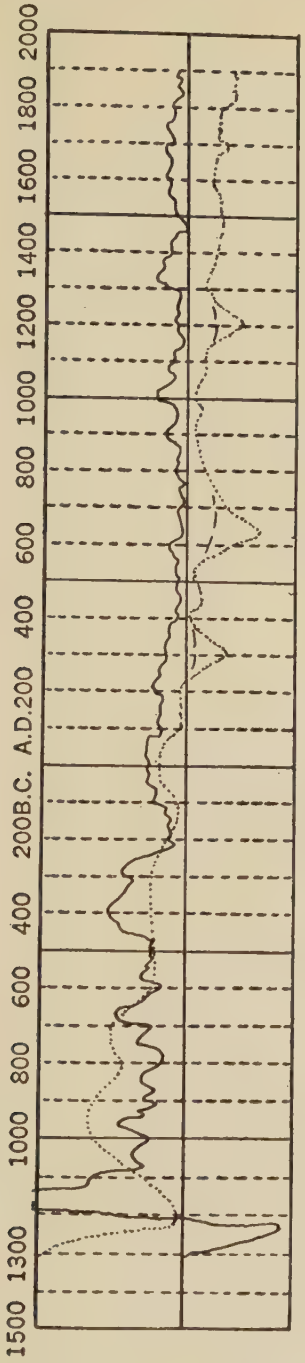

FIG. 56.—Changes of Climate in Western Asia (dotted line) and Growth of Trees in California (solid line). Reproduced from Ellsworth Huntington's "Civilization and Climate," Third Edition, Yale University Press, 1924, P. 318.

part of the world and then another had the advantage in these respects.

The Doubts of Forecasting.—At present we do not know how we may be tending in climate. Records of rainfall and runoff are relatively short and give no clear-cut indication of increase or decrease in average precipitation or of such other conditions that might influence flood flows. If the data were such as to indicate changes in the century or so covered by the longest accurate records at our disposal, we should still be in doubt as to whether such changes indicated a prolonged upward tendency or simply the upturn of one of the minor pulsations in a series, the general tendency of which was downward.

There is nothing to indicate that we shall be able to solve this riddle with any definiteness in the near future. The data now at our disposal, or that may be secured in the years to come, seem hopelessly inadequate for such a forecast. We must, however, always keep in mind the general condition outlined above, and not be surprised if the records of succeeding periods diverge more or less, and even quite substantially, from the records of the past.

This thought should certainly keep us from being too sanguine in our estimates. In many cases it should lead us to make more generous allowances for spillway channels and other such structures than would be arrived at by the simple consideration of the data in hand.

This condition also leads us from another angle to a refinement in language which has been previously noted, the appellation given to rare floods. It is easy to speak of a ten-year flood, a hundred-year flood and a thousand-year flood, meaning thereby the greatest floods that, on present evidence, may be expected to be equalled or exceeded on an average once in ten years or in a hundred years or in a thousand years.

A more accurate expression is to state that there is a ten per cent chance or a one per cent chance or 0.1 per cent chance of the occurrence of such floods in any given year. In other words, such estimates are based on the continuance of the conditions under which the data were collected and should apply to the immediate future only.

It must be recognized that in a thousand years and even

within a hundred years there may be changes or pulses in the climate which will increase or decrease the flood conditions, and no one should undertake to venture a prediction of how great a flood may occur in such a long interval.

On the other hand, the history of the world in the last three thousand years does not lead us to expect sudden changes in climate. Pulses must be expected and accepted when they come, but there is no reason to expect that any one pulse, or any change that occurs in the life time of one generation, will change the conditions so radically that intelligent estimates based on past experience will be no longer valuable.

CHAPTER XIX

METHODS OF FLOOD PROTECTION

In this chapter the attempt will be made merely to outline the most important methods of dealing with floods to reduce their destructiveness. These may be divided into four groups:

(1) Reducing flood volumes by storage.
(2) Increasing channel capacities.
(3) Providing by-pass channels.
(4) Levees and other local protective measures.

Some readers may expect forest planting and conservation to be on this list, but it is not included for the reason that there is no evidence that forest conditions are a substantial element in changing flood flows.

Reducing Flood Volumes by Storage.—Storage reservoirs have been built to control floods especially at Dayton, Ohio, and at San Antonio, Texas. It is to be expected that, as the country develops, many other applications of this method will be found advantageous. On the other hand, it is quite clear that there are many localities where this method, for one reason or another, is not applicable. In general, as was pointed out above, three per cent of the area must be fully controlled by such reservoirs to affect each two per cent reduction in flood quantities.

Reservoirs built for other purposes usually have more or less freeboard storage, that is, capacity to hold flood waters temporarily above their ordinary flow lines; and so far as this is the case they tend to reduce flood flows that would otherwise pass them.

Many recent dams have been provided with siphon spillways, Taintor gates and other equipment intended to maintain approximately constant levels during floods. As far as this purpose is accomplished, their value for flood prevention is destroyed.

In some cases it would no doubt pay to follow the opposite

course and, instead of destroying freeboard storage by such devices, deliberately increase it by building dams higher than otherwise necessary to provide a certain amount of storage available for reducing flood flows, and not to be used for any other purpose. A dam built in that way would serve a double purpose, first, its primary use; and second, the reduction of flood quantities. It would seem appropriate if the flood control element warranted building it in this way, that the property benefited by reduction of flood risk should contribute the additional cost of the higher dam.

Reducing Floods by Increasing Channel Capacities.—Increasing the capacity of flood channels has been carried out in many places. In the normal course of events these channels are contracted and reduced in capacity by the works of man for a certain period during which there is no very great flood, then there comes a larger flood that does damage, and afterward there is a housecleaning and the obstructions are removed.

Increased channel capacity through cities may be obtained by removing obstructions such as bridge piers, etc., by widening the channel, by deepening the channel, by making the channel smoother, thus increasing the coefficient of discharge, and by straightening the channel.

When stream channels are considerably straightened the velocity is increased, both because of the greater slope and because of the smaller amount of head required to get water around sharp bends; and if the bed of the stream is alluvial material, it may happen that straightening may be followed by scouring and deepening of the channel, which gives a further increase in capacity.

If the river is a navigable one, deepening by erosion of the bottom may lead to numerous changes some of which may be advantageous and some of them may not.

Reducing Floods by Providing By-pass Channels.—By-pass channels have been used in only a limited number of cases. There are natural ones on the Sacramento River in California, and on the lower Mississippi. Such natural channels tend to relieve the stress of the great floods upon that stream, but man may extend the system by appropriate works. Similar conditions no doubt exist in the lower parts of many other rivers in their natural condition.

At Tokio, Japan, there is an interesting case of bypass works on the River Arakawa, which flows through the lower part of the city and which formerly caused much flood damage. The catchment area is about 1,600 square miles and the maximum flood quantity is about 200,000 cfs. The bypass starts above the City where the river is tidal and where the flow is controlled by a masonry dam with ample ports, one of which is used for navigation. Ordinarily these are freely open but in time of flood they are closed so as to protect the old channel and limit the flow to its capacity.

The new flood channel is 14 miles long and varies in width from 1,500 to 1,800 feet. The excavated material amounting to 104 million cubic yards was used in forming dykes, something like 20 feet high, and slightly higher on the city side than on the countryside, and also in raising certain low land in the city.

The works, with auxiliary channels, occupy an area of 9 square miles from which the population and industries were removed as a preliminary.

Similar works have been built for the protection of the City of Osaka.

Reducing Floods by Building Levees, etc. Levees and other works for local protection are intended to keep a certain area from being flooded without reducing either the flood quantities or the flood heights. Levees have been generally used. The Mississippi River is the most conspicuous instance but there are many others. The construction of levees tends to narrow and control the river channel. It has been sometimes thought that this control would increase the velocity and lead to erosion of the bottom and so maintain the flood discharging capacity without raising flood levels.

This may happen in some cases, but it seems to be more commonly the case that the construction of levees, by decreasing the area of the flood channels, increase the flood heights. On the Mississippi River, for example, there is no doubt that the flood heights in recent years are materially greater than they were before levees were built, and it is thought that, as the levee system is perfected and completed, the flood heights will be still further increased.

If the levee system or any other system of flood control leads to a comparative security or to freedom from flooding through a

certain period, the natural tendency will be for people to occupy the land so protected; and if the protection fails in some great flood, the final loss may be greater than it would have been if no protection had been provided in the first place.

There is thus a heavy responsibility that goes with laying out protective works of this kind that may include encouraging people to occupy the land so protected.

One fundamental point will tend to minimize this danger and be helpful at other points. If people are encouraged to live above the highest flood levels, and to keep all their more valuable and destructible possessions in such places, and to travel back and forth to the low lands which are cultivated but not used for permanent residence, the danger of disaster will be greatly reduced.

It is difficult to say how far measures of this kind may be carried within economic limits. In narrower valleys, as for instance along the Connecticut River, this system has been followed since the country was occupied. The people live in farming villages on high land and go down to cultivate the meadows, which are not flooded often enough to prevent them from being used as productive farm land.

The range that could be covered by such an arrangement may be considerably increased at the present time and in the future by the construction of good roads and by the use of automobiles both to carry people back and forth and to move farm products to higher lands.

Certainly one of the most important means of reducing risk of future disaster is by reducing to the minimum the permanent occupation of areas whose protection is not complete.

Economic Limit of Flood Protection.—If all the conditions were accurately known, the economic limits of flood protection could be definitely computed. As a matter of calculation it would be at that point at which the sum of the construction cost and the value of the insurance against flood loss were at a minimum.

If we knew accurately the amount of damages that would result from a flood in excess of the amount provided and the amounts of the ten, one, and 0.1 per cent chance floods, the rest of the calculation would be easy. Estimates of the cost of taking care of various quantities of water would still be necessary,

but would ordinarily present no serious difficulty. Unfortunately we do not know and cannot know the amount of the flood damage, nor can we know what the flood quantities will be.

Estimates can be made on the best data available but these estimates must be regarded as tentative approximations that may vary more or less widely from such true figures as might be deduced from long-term accurate records if they existed.

If we had the data to make an accurate estimate, the procedure would be something like this:

The damage to be caused by a flood in excess of the amount provided for would be estimated. This damage may be taken as the sum in which flood insurance is to be written. Flood insurance as a business does not exist, but the annual value of the insurance may be estimated by multiplying the amount of the insurance by the per cent chance of the occurrence of a flood above the limit. The annual value of the insurance so obtained is then to be capitalized at the prevailing rate of interest. The amount represents the present value of the entire risk.

A Spillway Case as an Illustration.—Constructions of spillway capacity at a dam is profitable up to the point where the additional cost equals the saving in the present value of the insurance risk.

This may be illustrated by an actual case from the author's notebook. In this case there is a series of five small dams, one above the other in the same system. The names will be omitted, numbers being used instead.

In the first place, the conditions at each dam were thought out as far as possible in advance to determine what would happen to the dam if the estimated flow was exceeded and what would result from the release of the water held by it. In this case the dams were fortunately set up in such a way that the failure of one of the upper dams would not be likely to carry out the lower dam, but there would be the loss of the structure and a partial filling of the dams below with sediment, and demoralization of the system which was represented by estimated damages as indicated. The failure of the lowest dam would cause a destructive flood in the valley below, extending to several good sized villages.

The calculation of the insurance values in tabular form is set forth in the accompanying table:

ILLUSTRATIVE CALCULATION OF THE INSURANCE VALUE OF SPILLWAYS USED AS AN AID IN FORMING JUDGMENT AS TO THE SIZES TO BE PROVIDED

	Per cent chance of flood occurring in any one year	Annual value of insurance	Capitalized value of insurance	Cubic feet per second corresponding	Increase in value of insurance	Increase in capacity	Value per cubic foot per second additional capacity
Dam 1, Insurance, $200,000.....	1.0	$2,000	40,000	2100			
	0.5	1,000	20,000	2300	$20,000	200	100
	0.2	400	8,000	2600	12,000	300	40
	0.1	200	4,000	2800	4,000	200	20
	0.05	100	2,000	3100	2,000	300	7
Dam 2, Insurance, $1,000,000.....	0.5	5,000	100,000	2300			
	0.2	2,000	40,000	2600	60,000	300	200
	0.1	1,000	20,000	2800	20,000	200	100
	0.05	500	10,000	3100	10,000	300	33
	0.02	200	4,000	3400	6,000	300	20
Dam 3, Insurance, $2,000,000.....	0.2	4,000	80,000	2700			
	0.1	2,000	40,000	3000	40,000	300	133
	0.05	1,000	20,000	3300	20,000	300	67
	0.02	400	8,000	3600	12,000	300	40
	0.01	200	4,000	3900	4,000	300	13
Dam 4, Insurance, $3,000,000.....	0.1	3,000	60,000	2900			
	0.05	1,500	30,000	3200	30,000	300	100
	0.02	600	12,000	3500	18,000	300	60
	0.01	300	6,000	3900	6,000	300	20
Dam 5, Insurance, $10,000,000.....	0.1	10,000	200,000	2100			
	0.05	5,000	100,000	2400	100,000	300	333
	0.02	2,000	40,000	2800	60,000	400	150
	0.01	1,000	20,000	3100	20,000	300	67

Estimates of cost of enlarging the several spillways to the several sizes are required to complete the study. They are not shown in this table.

Even though such calculations must necessarily be based on inadequate data and be far from conclusive, they may nevertheless be helpful as aids to judgment. They may on the one hand prevent us from being satisfied with inadequate provisions and on the other they will tend to prevent large expenditures for capacities greatly in excess of probable requirements.

As a shorter method and without going through such calculations, it may be assumed that in providing for channel capacity through cities and towns, one should seldom be satisfied

with provision for less than the one per cent chance flood, and on the other hand, it will seldom be profitable to provide capacity for more than the 0.1 per cent chance flood.

In providing spillway capacity for reservoirs where great damage would follow failure by overtaxing spillway capacity, and taking into account the human limit in making estimates, it may be well to provide capacities greatly in excess, up to two or even three times the amounts computed by these methods.

CHAPTER XX

CONCLUSION

We have considered the data of flood flow that are available and have tried to find ways of making them tell their story. This has been taken up mainly from the standpoint of estimating the probable quantities of flood flows. It may be well now to review briefly some of the main points, and to set them out in their relations to each other.

The hydraulic engineer is said to be a man who trains wild and destructive rivers to lead quiet and useful lives. There are many hydraulic engineers. It would seem reasonable to hope that after a while all the rivers would be trained, and the flood problem would disappear. It is not the author's wish to disparage the capacity of his brothers. Many wonderful things have been done in the way of training rivers and more will follow, but there are limitations, and for some time yet the man who wants to be really safe from flood waters will do well to put his house on high ground.

Some day the engineers may turn the heat of Vesuvius into electricity and prevent the destructive flows of lava that have cost so many human lives in the course of centuries. But for the present no one knows just how to go about doing it. The great storms, and the flood flows that come from them, are as far from human control as Vesuvius lava. Man may dig wider and deeper channels for the water to flow in. He may cut off bends and straighten sides to let the water flow faster. He may build levees to hold flood waters in restricted channels. He may build detention reservoirs to hold back and spread out flood flows through more time. He may cut forests and plant others. But he cannot reduce the water quantities in any appreciable measure.

The necessary fundamental knowledge about floods, or a good deal of it, has been in the possession of some engineers for a

long time, one might almost say since the days of Noah. Yet obstruction of stream channels in populous communities and the building of homes and all sorts of human enterprises on low land that has been flooded within the memory of man, and that is certain to be flooded again and again, goes merrily on.

Keeping Out of Flood Areas.—The surprising thing is that each time a flood occurs so many intelligent people take it as an act of God rather than as something that grew out of their own acts (or perhaps of their fathers') and fail to see that it could have been anticipated and much of the damage prevented. And it is disappointing to see how many people who lose their all, or a large part of it, will go about reestablishing themselves in the same old locations where the same thing will happen again sooner or later. And their good neighbors will sympathize and help them in rebuilding. Even the Red Cross raises and distributes money to help. The state and federal governments make appropriations to repair flood damage, and money is spent in the inevitable track of a future flood.

Flood prevention work must be wisely directed as otherwise it may prove to be worse than useless. A levee that holds small floods, but is not high and strong enough to hold a large one, may inspire confidence in the minds of the people through a term of years while the levee functions, and so lead more people to live behind it, and ultimately bring greater disaster. The same thing may be said, with appropriate variations, for any kind of flood protection work.

Possible Flood Insurance.—Flood insurance would be a wonderful thing if it were possible. The factory mutual insurance companies have almost stopped destructive fires in the kind of property that they insure. They have done this by inspection. By their own representatives they have found the danger spots in factory property and have firmly insisted upon their removal. This phase of the factory mutuals has been of inestimable value in the long run. It has far outrun the value of the insurance which was the direct object of these companies.

There are difficulties in the way of flood insurance which may make it impracticable. At any rate, it does not exist at the present time. Its great value would lie in the visit of a trained inspector who would tell the applicant, if his situation warranted it, that his risk was too great and that he was either

not insurable or that his premium, if he were insured, must be very high. The educational value of such a responsible service would be beyond calculation. An inspection service without the insurance might not do. It would require the financial risk of the decision whether or not to undertake insurance to give it the necessary degree of responsibility and reliability.

In some respects the situation may be improving. There has been accumulating a mass of reliable data about flood flows that should make it possible to form a better idea of probable flood quantities and the periods of their recurrence. Data of this kind, consisting of a great number of items of information, are not of much use until they are organized in a way to make them tell their story. The collection of data in the United States has gone faster in the last decades than the analysis of the results, but there has been progress in this also, and a number of excellent papers have been published that have been and are of great assistance in this study.

Floods are nothing new. They are as old as civilization. Little floods come often, every year on every stream if you please, but big floods come at longer intervals. The bigger the flood the longer the average interval, but the interval is irregular and not fixed. A big flood is just as apt to follow another in the ensuing year as it is after any other time interval. There is, therefore, no warrant for the commonly expressed view that after a flood there will not be another for a century, or a generation, or within the life of the one making the prophecy.

All of the floods, through a term of years, great and small, tend to hold more or less closely to certain average values, and the variations from the mean follow more or less closely some law of probability. This law is not the normal law of error, as it is called, but is one of the skew types. It may seem a little intricate at first, but it is really not so complicated, thanks to Foster's work. The methods he has proposed and others available which are not too laborious may be depended upon to make the data from the relatively short record periods show as much as such data are capable of showing.

Value of Length of Record.—The shortness of the record periods is the real handicap. The longest record is only some eighty years, and only a few are more than thirty years. From

such short records one must form a judgment of probable or possible floods for a thousand years, or what is the equivalent, the chances down to one in a thousand, and even farther than that, of the occurrence of a very great flood in any one year. This defect of short records, however, is one that is slowly but surely being corrected as the years pass and as records of flow of many streams are being accumulated.

Flood quantities seem to go in cycles, or perhaps in pulses, the term used by Ellsworth Huntington in regard to climatic changes. Certainly such changes are observable in the records of the past, but no one has yet found the key to the succession that will permit estimates of future changes to be made. The uncertainty that goes with these pulses must be accepted as part of the inevitable uncertainty in all estimates of future flood quantities.

The use of data now available will permit estimates of flood quantities to be made of a certain degree of definiteness and accuracy. The data are much better for some parts of the country and for some streams than for others, and estimates will vary in probable accuracy accordingly. It can never be told in advance that there will be a great flood in the next year. The chance of its occurrence in any one year, or other definite period of time is as far as we know how to carry the estimate. Such estimates of chance of the occurrence of floods above set limits will be more definite and accurate for the little floods that occur frequently, and less and less accurate for the great and greater floods that occur only at long intervals. The estimate will best be stated as the percentage chance of the occurrence of a flood above a given limit within any one year.

The data at hand seem to warrant the idea that estimates for floods that recur on an average as often as once in ten years may be made with a satisfactory degree of accuracy for streams that have been gaged for a term of years, and with less accuracy for other streams. Most of the streams have not been gaged, and an estimate for such a stream, even though it is fairly accurate, is of relatively little value for the present purpose, because such floods are usually more or less well understood and provided for by present arrangements.

The estimate for the flood that will recur on an average of once in a hundred years is more difficult and less certain, and

much more important because commonly, but not always, it goes beyond the memory and personal experience of those who need to provide against the chance of its recurrence. This one per cent chance flood, as we call it, may be as a practical matter the most important point in the estimates and the one which will best repay close study.

The application of probability methods will often lead to results that seem quite definite and satisfactory, but it must not be forgotten that the cycle or pulse element is not and cannot be reflected in the work, and the best estimate may therefore, through no fault of the process, fail to represent the future correctly. That is to say, if there should be a general increase in general rainfall, such as Huntington's work indicates as taking place at intervals in the history of climate, or in the flood quantities, for which we have no historic basis but which we may fairly infer would follow, then the estimates would probably be exceeded. Under reverse conditions they would prove to be too high. These are matters beyond estimate at the present time. They can only be covered by a factor of safety to be added to the best estimate that can be made. Such a factor of safety should be used in all cases where the risk requires it, and may properly be varied, both with the apparent accuracy, or lack of accuracy, of data and estimate, and with the magnitude of the disaster that might follow a flood in excess of the amount of water provided for.

It is going a long way to estimate floods that will recur on an average less than once in a hundred years from the data of records that, at most, cover considerably less than a century. But we cannot stop because of the evidence—which may be considered conclusive—that there are very much greater floods that come at longer intervals. While the chance of the occurrence of such a greater flood in any one year is small, at most less than one per cent, the amount to be lost and to be insured against may be enormous, and the value of the risk, or insurance if insurance were available, may be so great as to require protective measures to be carried to the estimate and beyond.

Theoretically the most desirable result will be reached when the sum of the cost of the protective measures and the insurance is at a minimum. The calculation to establish that point as a practical matter may be too uncertain in several respects to be

dependable. Nevertheless the attempt to calculate it may be a material aid to an understanding of the problem and in reaching sound judgment. Doing it will lead to an attempt to estimate floods so large that the annual chance of their recurrence may be as little as one-tenth, or even one-hundredth of one per cent.

Estimates of such rare floods may be easily made with quite definite results by applying certain methods to the assembled data. There is choice of method, and different methods yield results that diverge more and more as the chance of recurrence in any one year becomes smaller. These estimates can be made, and they seem to serve a necessary purpose, but they are not to be taken too seriously. At best we must think that they might fall wide of the mark if there were any reliable way of testing them.

The Flood Beyond the Estimate.—It remains to mention a few well attested floods, most of them on small streams not otherwise gaged, that so far exceed what would otherwise be estimated as probable for streams of their sizes and conditions as to indicate that some explanation not at present in sight must be sought to account for them. The total number of such cases is small, but the facts are too firmly established to be passed over. On the other hand, the data relating to them are too few and too widely distributed in different parts of the country to permit of any satisfactory statistical study of this interesting subject.

All that can be done now to recognize these results is to give a preference for methods of estimate, other things being equal, which produce higher estimates for extreme values, and otherwise to use factors of safety above base estimates that may be thought to reflect, in some rough way at least, the chance of the occurrence of a still greater flood, such as is suggested by these few but most interesting cases.

We are apt to think of flood flows as consisting of water quantities. The water quantities, of course, come first and are most important, but great floods frequently carry great masses of solid matter both suspended and floating. The amount and character of these solid matters depend upon the size of the stream, the severity of the flood and the country from which the water is gathered.

In the east, floating material, bridges, houses, trees, etc., may be stopped in a narrow opening and clog it and raise the water much higher than it would otherwise rise. In all the arid and semi-arid west, where floods are infrequent, and the ground is easily washed, great quantities of sediment are carried by flood flows, and this sediment will be dropped as soon as a stream reaches flatter ground where the slope and velocity are less. These solid matters carried by flood flows frequently play a dominating part in what happens, a part that is apt to be overlooked when histories are considered long afterward.

In the case of the Mississippi River, and some other large sediment-carrying streams, the element of sediment may be almost controlling. Any plan of flood protection that fails to adequately provide for the permanent disposition of all the sediment that cannot be carried in the lower reaches of the river is bound to fail in the long run.

The subject is not exhausted by this discussion. Rather it is only fairly opened. It presents a most inviting field for further study. The interest in studying it may be increased by the knowledge of the tremendous importance of the subject in its bearings on the flood losses of life and property.

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TABLE I

VARIATION FACTORS FOR A NORMAL SERIES, BEING THE VALUES USED IN LAYING OUT PROBABILITY PAPER

Per cent of terms beyond limit at one end	Variation in terms of standard variation	Per cent of terms beyond limit at one end	Variation in terms of standard variation	Per cent of terms beyond limit at one end	Variation in terms of standard variation
50	0.000	10	1.282	0.28	2.770
49	0.025	9	1.340	0.27	2.782
48	0.050	8	1.405	0.26	2.794
47	0.075	7	1.475	0.25	2.807
46	0.100	6	1.556	0.24	2.820
45	0.126	5.0	1.645	0.23	2.834
44	0.151	4.5	1.694	0.22	2.848
43	0.176	4.0	1.750	0.21	2.863
42	0.202	3.5	1.811	0.20	2.878
41	0.228	3.0	1.880	0.19	2.894
40	0.253	2.9	1.895	0.18	2.910
39	0.279	2.8	1.911	0.17	2.929
38	0.305	2.7	1.927	0.16	2.948
37	0.332	2.6	1.944	0.15	2.968
36	0.358	2.5	1.961	0.14	2.989
35	0.385	2.4	1.979	0.13	3.011
34	0.412	2.3	1.997	0.12	3.035
33	0.440	2.2	2.016	0.11	3.062
32	0.468	2.1	2.035	0.10	3.090
31	0.496	2.0	2.054	0.09	3.121
30	0.524	1.9	2.075	0.08	3.155
29	0.553	1.8	2.098	0.07	3.194
28	0.583	1.7	2.120	0.06	3.239
27	0.613	1.6	2.144	0.05	3.291
26	0.643	1.5	2.169	0.04	3.353
25	0.674	1.4	2.197	0.03	3.431
24	0.706	1.3	2.226	0.02	3.540
23	0.739	1.2	2.257	0.015	3.614
22	0.772	1.1	2.290	0.010	3.718
21	0.807	1.0	2.326	0.008	3.774
20	0.842	0.9	2.364	0.006	3.845
19	0.878	0.8	2.409	0.004	3.943
18	0.915	0.7	2.456	0.003	4.012
17	0.954	0.6	2.512	0.002	4.107
16	0.995	0.5	2.575	0.0015	4.172
15	1.036	0.45	2.611	0.0010	4.264
14	1.080	0.40	2.651	0.0005	4.417
13	1.126	0.35	2.696	0.0001	4.751
12	1.175	0.30	2.747	0.00001	5.200
11	1.227	0.29	2.758	0.000001	5.613

TABLE II

Logarithmic Skew Curve Factors

Multiply Coefficient of Variation by These and Add to or Subtract from the Mean

Coefficient of skew	Terms over mean per cent	Per cent of term above limit									Corresponding coefficient variation
		99 −	95 −	80 −	50 −	20 +	5 +	1 +	0.1 +	0.01 +	
0	50.0	2.32	1.64	0.84	0	0.84	1.64	2.32	3.09	3.72	0
0.1	49.4	2.25	1.62	0.85	0.02	0.84	1.67	2.40	3.24	3.96	0.03
0.2	48.7	2.18	1.59	0.85	0.03	0.83	1.71	2.48	3.39	4.20	0.06
0.3	48.1	2.12	1.56	0.85	0.05	0.83	1.74	2.56	3.55	4.45	0.10
0.4	47.5	2.05	1.53	0.85	0.06	0.82	1.76	2.64	3.72	4.72	0.13
0.5	46.9	1.99	1.50	0.85	0.08	0.82	1.79	2.72	3.90	5.00	0.16
0.6	46.3	1.92	1.47	0.85	0.09	0.81	1.81	2.80	4.08	5.30	0.20
0.7	45.6	1.86	1.44	0.85	0.11	0.80	1.84	2.89	4.28	5.64	0.23
0.8	45.0	1.80	1.41	0.85	0.12	0.79	1.86	2.97	4.48	6.00	0.27
0.9	44.4	1.73	1.38	0.85	0.14	0.77	1.88	3.06	4.69	6.37	0.30
1.0	43.7	1.68	1.34	0.84	0.15	0.76	1.90	3.15	4.92	6.77	0.33
1.1	43.1	1.62	1.31	0.84	0.17	0.75	1.92	3.24	5.16	7.23	0.37
1.2	42.5	1.56	1.28	0.83	0.18	0.74	1.94	3.33	5.40	7.66	0.41
1.3	41.9	1.51	1.25	0.83	0.19	0.72	1.96	3.41	5.64	8.16	0.44
1.4	41.3	1.46	1.22	0.82	0.20	0.71	1.98	3.50	5.91	8.66	0.48
1.5	40.7	1.41	1.19	0.81	0.22	0.69	1.99	3.59	6.18	9.16	0.51
1.6	40.1	1.36	1.16	0.81	0.23	0.67	2.01	3.69	6.48	9.79	0.55
1.7	39.5	1.32	1.13	0.80	0.24	0.66	2.02	3.78	6.77	10.40	0.59
1.8	38.9	1.27	1.10	0.79	0.25	0.64	2.03	3.88	7.09	11.07	0.62
1.9	38.3	1.23	1.07	0.78	0.26	0.62	2.04	3.98	7.42	11.83	0.66
2.0	37.7	1.19	1.05	0.77	0.27	0.61	2.05	4.07	7.78	12.60	0.70
2.1	37.1	1.15	1.02	0.76	0.28	0.59	2.06	4.17	8.13	13.35	0.74
2.2	36.5	1.11	0.99	0.75	0.29	0.57	2.07	4.27	8.54	14.30	0.78
2.3	35.9	1.07	0.96	0.74	0.30	0.55	2.07	4.37	8.95	15.25	0.82
2.4	35.3	1.03	0.94	0.73	0.31	0.53	2.08	4.48	9.35	.....	0.86
2.5	34.7	1.00	0.91	0.72	0.31	0.51	2.08	4.58	9.75	.....	0.90
2.6	34.1	0.97	0.89	0.71	0.32	0.49	2.09	4.68	10.15	.....	0.94
2.7	33.5	0.94	0.86	0.69	0.33	0.47	2.09	4.78	10.65	.....	0.98
2.8	32.9	0.91	0.84	0.68	0.33	0.45	2.09	4.89	11.20	.....	1.03
2.9	33.3	0.87	0.82	0.67	0.34	0.43	2.09	5.01	11.75	.....	1.08
3.0	31.8	0.84	0.79	0.66	0.34	0.41	2.08	5.11	12.30	.....	1.12
3.2	30.6	0.78	0.74	0.64	0.35	0.37	2.06	5.35	13.50	.....	1.22
3.4	29.4	0.73	0.69	0.61	0.36	0.32	2.04	5.58	.....	.....	1.33
3.6	28.2	0.67	0.65	0.58	0.36	0.28	2.02	5.80	.....	.....	1.44
3.8	27.0	0.62	0.61	0.55	0.36	0.23	1.98	6.10	.....	.....	1.57
4.0	25.7	0.58	0.56	0.52	0.36	0.19	1.95	6.50	.....	.....	1.70
4.5	22.2	0.48	0.47	0.45	0.35	0.10	1.79	7.30	.....	.....	2.10
5.0	19.2	0.40	0.40	0.39	0.34	0	1.60	8.20	.....	.....	2.50

Adjusted Skew = Computed Skew $(1+\frac{8.5}{n})$.

The figures in the last column show the value of the coefficient of variation that, in connection with the coefficient of skew shown in the first column will produce plotting point of a line that is straight on log. probability paper.

TABLE III

Foster's Skew Curve Factors

Multiply Coefficient Variation by These and Add to or Subtract from Mean

(Type I, Transactions Am. Soc. C. E. 87, p. 196)

Coefficient of skew	Terms over mean per cent	Per cent of terms above limit										
		99 −	95 −	80 −	50 −	20 +	5 +	1 +	0.1 +	0.01 +	0.001 +	0.0001 +
0	50.0	2.08	1.64	0.92	0	0.92	1.64	2.08	2.39	2.53	2.59	2.62
0.2	48.4	1.91	1.56	0.93	0.05	0.89	1.72	2.25	2.66	2.83	2.94	3.00
0.4	46.7	1.75	1.47	0.93	0.09	0.87	1.79	2.42	2.95	3.18	3.35	3.44
0.6	45.1	1.59	1.38	0.92	0.13	0.85	1.85	2.58	3.24	3.59	3.80	3.92
0.8	43.4	1.44	1.30	0.91	0.17	0.83	1.90	2.75	3.55	4.00	4.27	4.43
1.0	41.8	1.30	1.21	0.89	0.21	0.80	1.95	2.92	3.85	4.42	4.75	4.95
1.2	40.1	1.17	1.12	0.86	0.25	0.77	1.99	3.09	4.15	4.83	5.25	5.50
1.4	38.5	1.06	1.03	0.83	0.29	0.73	2.03	3.25	4.45	5.25	5.75	6.05
1.6	36.8	0.96	0.95	0.80	0.32	0.69	2.07	3.40	4.75	5.67	6.25	6.65
1.8	35.2	0.87	0.87	0.76	0.35	0.64	2.10	3.54	5.05	6.08	6.75	7.2
2.0	33.5	0.80	0.79	0.71	0.37	0.58	2.13	2.67	5.35	6.50	7.25	7.8

TABLE IV

(Type III, Transactions Am. Soc. C. E. 87, pp. 162 and 199)

0	50.0	2.33	1.64	0.84	0	0.84	1.64	2.33	3.09	3.73	4.27	4.76
0.2	48.7	2.18	1.58	0.85	0.03	0.83	1.69	2.48	3.38	4.16	4.84	5.48
0.4	47.3	2.03	1.51	0.85	0.06	0.82	1.74	2.62	3.67	4.60	5.42	6.24
0.6	46.0	1.88	1.45	0.86	0.09	0.80	1.79	2.77	3.96	5.04	6.01	7.02
0.8	44.7	1.74	1.38	0.86	0.13	0.78	1.83	2.90	4.25	5.48	6.61	7.82
1.0	43.3	1.59	1.31	0.86	0.16	0.76	1.87	3.03	4.54	5.92	7.22	8.63
1.2	42.0	1.45	1.25	0.85	0.19	0.74	1.90	3.15	4.82	6.37	7.85	9.45
1.4	40.7	1.32	1.18	0.84	0.22	0.71	1.93	3.28	5.11	6.82	8.50	10.28
1.6	39.4	1.19	1.11	0.82	0.25	0.68	1.96	3.40	5.39	7.28	9.17	11.12
1.8	38.1	1.08	1.03	0.80	0.28	0.64	1.98	3.50	5.66	7.75	9.84	11.96
2.0	36.8	0.99	0.95	0.78	0.31	0.61	2.00	3.60	5.91	8.21	10.51	12.81
2.2	35.5	0.90	0.89	0.75	0.33	0.58	2.01	3.70	6.20			
2.4	34.3	0.83	0.82	0.71	0.35	0.54	2.01	3.78	6.47			
2.6	33.0	0.77	0.76	0.68	0.37	0.51	2.01	3.87	6.73			
2.8	31.9	0.71	0.71	0.65	0.38	0.47	2.02	3.95	6.99			
3.0	30.8	0.67	0.66	0.62	0.40	0.42	2.02	4.02	7.25			

Adjusted Skew = Computed Skew $(1+\frac{8.5}{n})$.

TABLE V

VALUES OF CORRECTION FACTORS FOR COEFFICIENTS OF SKEW $\left(1+\frac{8.5}{n}\right)$

Number of terms	Factors	Number of terms	Factors	Number of terms	Factors
11	1.775	36	1.236	61	1.139
12	1.708	37	1.230	62	1.137
13	1.653	38	1.224	63	1.135
14	1.608	39	1.218	64	1.133
15	1.567	40	1.212	65	1.131
16	1.530	41	1.207	66	1.129
17	1.500	42	1.202	67	1.127
18	1.472	43	1.198	68	1.125
19	1.447	44	1.193	69	1.123
20	1.425	45	1.189	70	1.122
21	1.405	46	1.185	71	1.120
22	1.386	47	1.181	72	1.118
23	1.370	48	1.177	73	1.117
24	1.354	49	1.174	74	1.115
25	1.340	50	1.170	75	1.113
26	1.327	51	1.167	76	1.112
27	1.315	52	1.164	77	1.111
28	1.303	53	1.161	78	1.109
29	1.293	54	1.158	79	1.108
30	1.283	55	1.155	80	1.107
31	1.274	56	1.152		
32	1.265	57	1.149		
33	1.257	58	1.147		
34	1.250	59	1.144		
35	1.243	60	1.142		

TABLE VI

FULLER FACTORS SHOWING RATIO OF MAXIMUM RATE TO AVERAGE ONE-DAY FLOOD FLOWS

$$* \text{Factor} = 1 + \frac{2}{A^{0.3}}$$

Area in square miles	Factor	Area in square miles	Factor	Area in square miles	Factor
1	3.00	102	1.50	2,550	1.19
2	2.62	141	1.45	3,050	1.18
3	2.44	212	1.40	3,700	1.17
4	2.32	330	1.35	4,500	1.16
5	2.23	550	1.30	5,700	1.15
6	2.17	620	1.29	7,000	1.14
7	2.11	700	1.28	9,000	1.13
8	2.07	790	1.27	12,000	1.12
9	2.03	900	1.26	16,000	1.11
10	2.00	1030	1.25	21,000	1.10
14	1.90	1170	1.24	30,000	1.09
21	1.80	1350	1.23	45,000	1.08
33	1.70	1570	1.22	71,000	1.07
55	1.60	1830	1.21	117,000	1.06
74	1.55	2150	1.20	220,000	1.05

* Transactions Am. Soc. C. E. Vol. LXXVII, p. 573 (1914).
A = Area in square miles.

TABLE VII

Plotting Points for Probability Paper for Series Ranging from 13 to 40 Terms

Terms in Record

13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
3.85	3.57	3.33	3.13	2.94	2.78	2.63	2.50	2.38	2.27	2.17	2.08	2.00	1.92	1.85	1.79	1.72	1.67	1.61	1.56	1.52	1.47	1.43	1.39	1.35	1.32	1.28	1.25
11.54	10.71	10.00	9.38	8.82	8.33	7.89	7.50	7.14	6.82	6.52	6.25	6.00	5.77	5.56	5.36	5.17	5.00	4.84	4.69	4.55	4.41	4.29	4.17	4.05	3.95	3.85	3.75
19.23	17.86	16.67	15.62	14.71	13.89	13.16	12.50	11.90	11.36	10.87	10.42	10.00	9.62	9.26	8.93	8.62	8.33	8.06	7.81	7.58	7.35	7.14	6.94	6.76	6.58	6.41	6.25
26.92	25.00	23.33	21.87	20.59	19.44	18.42	17.50	16.67	15.91	15.22	14.58	14.00	13.46	12.96	12.50	12.07	11.67	11.29	10.94	10.61	10.29	10.00	9.72	9.46	9.21	8.97	8.75
34.62	32.14	30.00	28.12	26.47	25.00	23.68	22.50	21.43	20.45	19.57	18.75	18.00	17.31	16.67	16.07	15.52	15.00	14.52	14.06	13.64	13.24	12.86	12.50	12.16	11.84	11.54	11.25
42.31	39.29	36.67	34.37	32.35	30.56	28.95	27.50	26.19	25.00	23.91	22.92	22.00	21.15	20.37	19.64	18.97	18.33	17.74	17.19	16.67	16.18	15.71	15.28	14.86	14.47	14.10	13.75
50.00	46.43	43.33	40.62	38.24	36.11	34.21	32.50	30.95	29.55	28.26	27.08	26.00	25.00	24.07	23.21	22.41	21.67	20.97	20.31	19.70	19.12	18.57	18.06	17.57	17.11	16.67	16.25
57.69	53.57	50.00	46.87	44.12	41.67	39.47	37.50	35.71	34.09	32.61	31.25	30.00	28.85	27.78	26.79	25.86	25.00	24.19	23.44	22.73	22.06	21.43	20.83	20.27	19.74	19.23	18.75
65.38	60.71	56.67	53.12	50.00	47.22	44.74	42.50	40.48	38.64	36.96	35.42	34.00	32.69	31.48	30.36	29.31	28.33	27.42	26.56	25.76	25.00	24.29	23.61	22.97	22.37	21.79	21.25
73.08	67.86	63.33	59.37	55.88	52.78	50.00	47.50	45.24	43.18	41.30	39.58	38.00	36.54	35.19	33.93	32.76	31.67	30.65	29.69	28.79	27.94	27.14	26.39	25.68	25.00	24.36	23.75
80.77	75.00	70.00	65.62	61.76	58.33	55.26	52.50	50.00	47.73	45.65	43.75	42.00	40.38	38.89	37.50	36.21	35.00	33.87	32.81	31.82	30.88	30.00	29.17	28.38	27.63	26.92	26.25
88.46	82.14	76.67	71.87	67.65	63.89	60.53	57.50	54.76	52.27	50.00	47.92	46.00	44.23	42.59	41.07	39.66	38.33	37.10	35.94	34.85	33.82	32.86	31.94	31.08	30.26	29.49	28.75
96.15	89.29	83.33	78.12	73.53	69.44	65.79	62.50	59.52	56.82	54.35	52.08	50.00	48.08	46.30	44.64	43.10	41.67	40.32	39.06	37.88	36.76	35.71	34.72	33.78	32.89	32.05	31.25
	96.43	90.00	84.37	79.41	75.00	71.05	67.50	64.29	61.36	58.70	56.25	54.00	51.92	50.00	48.21	46.55	45.00	43.55	42.19	40.91	39.71	38.57	37.50	36.49	35.53	34.62	33.75
		96.67	90.62	85.29	80.56	76.32	72.50	69.05	65.91	63.04	60.42	58.00	55.77	53.70	51.79	50.00	48.33	46.77	45.31	43.94	42.65	41.43	40.28	39.19	38.16	37.18	36.25
			96.87	91.18	86.11	81.58	77.50	73.81	70.45	67.39	64.58	62.00	59.62	57.41	55.36	53.45	51.67	50.00	48.44	46.97	45.59	44.29	43.06	41.89	40.79	39.74	38.75
				97.06	91.67	86.84	82.50	78.57	75.00	71.74	68.75	66.00	63.46	61.11	58.93	56.90	55.00	53.23	51.56	50.00	48.53	47.14	45.83	44.59	43.42	42.31	41.25
					97.22	92.11	87.50	83.33	79.55	76.09	72.92	70.00	67.31	64.81	62.50	60.35	58.33	56.45	54.69	53.03	51.47	50.00	48.61	47.30	46.05	44.87	43.75
						97.37	92.50	88.10	84.09	80.43	77.08	74.00	71.15	68.52	66.07	63.79	61.67	59.68	57.81	56.06	54.41	52.86	51.39	50.00	48.68	47.44	46.25
							97.50	92.86	88.64	84.78	81.25	78.00	75.00	72.22	69.64	67.24	65.00	62.90	60.94	59.09	57.35	55.71	54.17	52.70	51.32	50.00	48.75
								97.62	93.18	89.13	85.42	82.00	78.85	75.93	73.21	70.69	68.33	66.13	64.06	62.12	60.29	58.57	56.94	55.41	53.95	52.56	51.25
									97.73	93.48	89.58	86.00	82.69	79.63	76.79	74.14	71.67	69.35	67.19	65.15	63.24	61.43	59.72	58.11	56.58	55.13	53.75
										97.83	93.75	90.00	86.54	83.33	80.36	77.59	75.00	72.58	70.31	68.18	66.18	64.29	62.50	60.81	59.21	57.69	56.25
											97.92	94.00	90.38	87.04	83.93	81.03	78.33	75.81	73.44	71.21	69.12	67.14	65.28	63.51	61.84	60.26	58.75
												98.00	94.23	90.74	87.50	84.48	81.67	79.03	76.56	74.24	72.06	70.00	68.06	66.22	64.47	62.82	61.25
													98.08	94.44	91.07	87.93	85.00	82.26	79.69	77.27	75.00	72.86	70.83	68.92	67.11	65.38	63.75
														98.15	94.64	91.38	88.33	85.48	82.81	80.30	77.94	75.71	73.61	71.62	69.74	67.95	66.25
															98.21	94.83	91.67	88.71	85.94	83.33	80.88	78.57	76.39	74.32	72.37	70.51	68.75
																98.28	95.00	91.94	89.06	86.36	83.82	81.43	79.17	77.03	75.00	73.08	71.25
																	98.33	95.16	92.19	89.39	86.76	84.29	81.94	79.73	77.63	75.64	73.75
																		98.39	95.31	92.42	89.71	87.14	84.72	82.43	80.26	78.21	76.25
																			98.44	95.45	92.65	90.00	87.50	85.14	82.89	80.77	78.75
																				98.48	95.59	92.86	90.28	87.84	85.53	83.33	81.25
																					98.53	95.71	93.06	90.54	88.16	85.90	83.75
																						98.57	95.83	93.24	90.79	88.46	86.25
																							98.61	95.95	93.42	91.03	88.75
																								98.65	96.05	93.59	91.25
																									98.68	96.15	93.75
																										98.72	96.25
																											98.75

TABLE VIII

CALCULATION OF A SERIES THAT WILL PLOT AS A STRAIGHT LINE ON LOGARITHMIC PROBABILITY PAPER

Percentage position of terms	Relative distance from center	Numbers to be used as logarithms in this proportion	Numbers corresponding to these logarithms	The same divided by the average of the preceding column	The squares of the differences	The cubes of the differences
2	2.054	0.088,382	1.2257	1.2200	0.0484	+0.01065
6	1.556	0.066,954	1.1667	1.1613	.0260	.00420
10	1.282	0.055,164	1.1354	1.1301	.0169	.00220
14	1.082	0.046,558	1.1131	1.1079	.0116	.00126
18	0.915	0.039,372	1.0949	1.0898	.0079	.00071
22	0.772	0.033,219	1.0795	1.0745	.0056	.00041
26	0.643	0.027,668	1.0658	1.0598	.0036	.00021
30	0.524	0.022,547	1.0533	1.0484	.0023	.00011
34	0.412	0.017,728	1.0417	1.0368	.0014	.00005
38	0.305	0.013,124	1.0307	1.0259	.0007	.00002
42	0.202	0.008,692	1.0202	1.0154	.0002	.00000
46	0.100	0.004,303	1.0100	1.0053	.0000	.00000
50	.....	.....	1.0000	.9953	.0000	.00000
54	.....	.....	.9901	.9855	.0002	.00000
58	.....	.....	.9802	.9756	.0006	−0.00001
62	.....	.....	.9702	.9657	.0012	−.00004
66	.....	.....	.9600	.9555	.0020	−.00009
70	.....	.....	.9494	.9450	.0030	−.00017
74	.....	.....	.9383	.9339	.0044	−.00029
78	.....	.....	.9264	.9221	.0061	−.00048
82	.....	.....	.9133	.9090	.0083	−.00075
86	.....	.....	.8984	.8942	.0112	−.00119
90	.....	.....	.8807	.8766	.0153	−.00188
94	.....	.....	.8571	.8531	.0215	−.00315
98	.....	.....	.8159	.8121	.0353	−.00662
Sum.....	.....	.....	25.1170	24.9988	.2337	0.00515

$$\text{C.V.} = \sqrt{\frac{.2337}{25-1}} = 0.0987$$

$$\text{C.S. comp.} = \frac{0.00515}{(25-1)\,\text{C.V.}^3} = 0.223$$

$$\text{C.S. adj.} = 0.223\left(1+\frac{85}{25}\right) = 0.299.$$

TABLE IX

COMPUTATION OF FACTORS TO BE USED FOR SEVERAL POINTS FOR THE SERIES IN TABLE VIII

Percentage position of point	Relative distance from center	Numbers in this ratio to be used as logarithms	Corresponding number	Same divided by average value of terms in the whole series	Variations in terms of C. V.
0.01	3.718	0.159,983	1.4454	1.4387	+4.445
0.1	3.090	0.132,960	1.3582	1.3519	3.566
1	2.324	.100,000	1.2589	1.2530	2.564
5	1.643	.070,697	1.1768	1.1713	1.736
20	0.842	.036,231	1.0870	1.0819	0.830
50	.....	.....	1.000	.9953	− .048
80	.....	.....	.9200	.9157	.854
95	.....	.....	.8497	.8458	1.562
99	.....	.....	.7943	.7911	2.117

It will be noted that the computations of the logarithms and numbers are only extended to the first half of the terms. The remaining terms are taken as reciprocals of those first found.

This is a sample series, one of 14 that were used. In the second series, the numbers used for logarithms in the first series were multiplied by two, and the terms were therefore the squares of the corresponding terms of the first series.

The third series was based on cubes, and the power was extended (with a few items omitted) to the twentieth power in the last series. The calculations were largely done mechanically and were checked in several ways. A summary of some of the results for the several series is given in the following table:

TABLE X

TABULAR STATEMENT OF DATA FOR FOURTEEN SERIES OF TWENTY-FIVE TERMS EACH THAT PLOT STRAIGHT ON LOGARITHMIC PROBABILITY PAPER, SHOWING THE FACTORS BY WHICH THE C. V. MUST BE MULTIPLIED AT THE VARIOUS POSITIONS STATED

Series Number	C. V.	C. S. adj.	Factors for use at percentages stated									Per Cent Terms above mean
			0.01%	0.1%	1%	5%	20%	50%	80%	95%	99%	
			+	+	+	+	+	−	−	−	−	
0	0	0	3.718	3.090	2.324	1.643	0.842	0	0.842	1.643	2.324	50.00
1	0.099	0.299	4.445	3.566	2.564	1.736	0.830	0.048	0.854	1.562	2.117	48.11
2	0.198	0.600	5.304	4.091	2.805	1.813	0.807	0.093	0.854	1.469	1.920	46.23
3	0.299	0.895	6.344	4.694	3.058	1.883	0.776	0.137	0.847	1.378	1.737	44.40
4	0.401	1.192	7.62	5.38	3.318	1.943	0.737	0.179	0.834	1.285	1.569	42.54
5	0.506	1.49	9.12	6.15	3.587	1.993	0.693	0.215	0.816	1.195	1.418	40.77
6	0.614	1.78	10.94	7.03	3.861	2.033	0.646	0.249	0.793	1.108	1.281	39.05
7	0.725	2.07	13.13	8.01	4.141	2.062	0.596	0.277	0.764	1.026	1.162	37.27
8	0.839	2.34	15.75	9.11	4.420	2.079	0.542	0.303	0.735	0.950	1.051	35.62
9	0.954	2.64	.....	10.36	4.717	2.093	0.489	0.323	0.706	0.881	0.957	34.00
10	1.072	2.89	.....	11.75	5.006	2.092	0.435	0.339	0.675	0.816	0.873	32.50
11	1.197	3.16	.....	13.25	5.278	2.075	0.380	0.350	0.642	0.754	0.796	30.85
13	1.450	3.61	.....	.....	5.832	2.023	0.277	0.361	0.579	0.650	0.673	28.21
15	1.706	4.01	.....	.....	6.563	1.953	0.186	0.365	0.523	0.567	0.579	25.60
20	2.335	4.81	.....	.....	7.79	1.703	0.008	0.346	0.413	0.425	0.428	20.42

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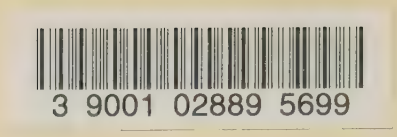
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